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48V BATTERY MANAGEMENT UNIT

Master of Science Thesis

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## ABSTRACT

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Battery management system design and application are the most important issues in power application unit. In dynamic system, a set of battery pack comprised with multiple cells are used to provide a required output voltage, where the performance and reliability of batteries are seriously concerned. A smart and adaptive battery management system is able to monitor battery cells in real-time, also to control the power operation on batteries. Therefore, with the help of battery management system, not only the batteries could be working under control, the safety issue of batteries is guaranteed as well.

This thesis aims to design a 48V power unit with 12 cells of lithium-ion batteries. A battery management system with LTC 6803-2 is applied to give a real-time monitor on each cell's voltage, state of charge and operation status. Besides, a graphic user interface is designed in software to implement all function in the aspect of users. Based on all the measurement results displayed on screen in real-time, a user is able to make a decision on batteries performance and then put forward controlling on batteries. This study is one part of an intelligent adaptive battery management system, some thoughts are proposed from this thesis, which are contributed to the future intensive research.

## **PREFACE**

The work presented in this thesis was done in Tampere, Finland while working for the RF Communication Circuits Laboratory (RFCC), Battery Management System (BMS) team at Tampere University of Technology (TUT). I would like to thank everybody at RFCC especially the BMS team members for their help and support during the system configuration, during the measurements and during the writing process of this work. Foremost, I would like to thank Professor Nikolay T. Tchamov, for the position he provided to work and research in RFCC laboratory as well as his guidance and support on my project work and thesis writing.

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## TERMS AND DEFINITIONS

BMS	Battery Management System
LIR	Lithium Ion Rechargeable battery
EV	Electrical Vehicles
OCV	Open Circuit Voltage
CCV	Closed Circuit Voltage
CV	Constant Voltage
CC	Constant Current
SoC	State of Charge
SoH	State of Health
GUI	Graphic User Interface
SPI	Serial Peripheral Interface

# 1. INTRODUCTION

Rechargeable batteries have the features to be charged or discharged repeatedly so as to be counted as a quite economic power supply. They are widely used and greatly favored for decades. However, due to the stored energy, battery safety, service life, state of charge, and state of health such inherent problems[18][21], an external intelligent system is needed to control and improve the performance of batteries, which is called the Battery Management System (BMS).

BMS is the link between batteries and users, and its main object is the rechargeable battery. Once operated, the BMS would monitor the status of battery cells such as cell temperature, cell voltage, charging or discharging current, and so on. BMS helps to prolong the battery service life as well as to improve the performance, which is one of its main merits. More details about the operation and merits of a BMS are elaborated in Chapter 3.

The main purpose of this project is to build up a power supply with its monitor system to provide a 48V's output voltage and provides a well-working management on it as well. The lithium-ion batteries are used as the model batteries. Since one single battery could supply a voltage as high as 4.2V, there are 12 cells of them that are connected in series to provide a maximum voltage up to 50.4V. The monitor system should be able to check and detect performance of all battery cells during the whole time. It detects the cell voltages from the battery pack, and then gives feedback in form of cell voltage and cell state of charge to the users, based on which the user can give a decision on batteries' performance. Furthermore, a graphic user interface is designed for the users to receive the feedback from monitor and to control the power system in a more straightforward and convenient way.

Therefore, the main target of this project is both to construct the battery management system on a hardware way, and to design its relevant user interface to test the function on a software way. Furthermore, a verification on the software function and accuracy should be made to certificate the whole system fully achieves all function and the results are reliable.

The background theory of lithium-ion battery as well as general basic function of BMS is introduced in Chapter 2. Chapter 3 is dedicated on the electrical function of battery management system circuit. Battery monitor LTC 6803-2 from Linear Technology is applied in this project, and this chapter would give a detailed description on its operating characteristics both on electrical configuration aspect and data communication aspect. Its application merits and limitation would be introduced in this chapter as well. Besides, this chapter also depicts the configuration of the whole system. From the point

of view of hardware, how the battery stack is constructed and how each battery cell is mapping to the BMS electrical board would be represented. Correspondingly, the software design is presented in Chapter 4. Chapter 5 confirms the accuracy of measurement by BMS by comparisons with digital multimeter, and chapter 6 gives a conclusion of the project and comes up with the future research on BMS.

## **2. BATTERY BACKGROUND**

Rechargeable batteries, known also as secondary batteries, are the type of batteries that can be charged for limited cycles. They are used in concert with matched chargers. Rechargeable batteries are widely used for the merits of economic and environmental natures. Nowadays, the common rechargeable batteries can be charged for about 1000 cycles. At present market, there are five kinds of rechargeable batteries in use, they are nickel cadmium battery, nickel metal hydride battery, lithium ion battery, lead acid battery and nickel iron battery. In this battery management system application, it is the lithium-ion batteries that are used.

### **2.1. Basic concepts of rechargeable lithium-ion battery**

Lithium-ion rechargeable battery is one kind of high performance batteries, which works based on the ions movement between cathode and anode. Ions get deintercalated from anode and intercalated to the cathode during charging, and the other way round for discharging.

Throughout the battery evolution, lithium-ion battery wins out of other batteries for its portable, environmental friendly, high energy-densities, and long cycling-life features. Among the commercial batteries, lithium-ion battery has the lightest metals compared to other batteries, also it has the largest specific energy per weight and specific energy per volume[1]. With an extraordinarily high energy density, it is capable to give a high average output voltage. Also, lithium-ion battery has a quite low self-discharge rate. Specifically, for the batteries with high quality, the self-discharge rate can be as low as 2%[18]. Furthermore, this kind of battery does not have battery memory effect at all. Basically, for batteries such as nickel metal based, without a complete charging or discharging over a long period of time, batteries would ‘memorize’ this habit and the capacity would decrease as a consequence. The lithium-ion battery, however, does not have such performance. Just because of such merits described above, lithium-ion batteries are greatly commonly utilized in mobile phones, laptops, base stations, and so on.

However, lithium-ion batteries have potential safety risks of explosion or fire in case of overcharge and over temperature[20]. Additionally, overcharge and overdischarge would intrinsically bring much harm to the batteries. Hence this can be seen, the need for BMS to protect batteries and enhance the performance is absolutely necessary [21].



### 2.1.1. Types of lithium-ion batteries

Generally, based on the cathode materials, there are different kinds of lithium-ion batteries. Table 2.1 gives the list of the lithium-ion family on their chemical materials, target applications and the features. Specially, it should be noted that the LT type of battery, which is at the last row of the table, uses the titanate material at the anode.

**Table 2.1.** List of different types of lithium-ion batteries[22]

Chemical Technology	Applications	Features
Lithium Cobalt Oxide (LCO)	cell phones, cameras and laptops	high capacity, but less safe
Lithium Manganese Oxide(LMO)	electrical bi-cycles, electrical vehicles(EV)	lower capacity but higher specific power and long life, most safe
Lithium Iron Phosphate(LFP)		
Lithium Nickel Manganese Cobalt Oxide (NMC)		
Lithium Nickel Cobalt Aluminum Oxide (NCA)	automotive, electrical grid, powertrain, bus	high output voltage, short charging time, long life and safe
Lithium Titanate(LT)		

The lithium-cobalt battery is made up of a cobalt oxide cathode and a graphite carbon anode. It is able to provide a relatively high specific energy, or capacity in another word. However, it has a shorter life span and less safety compared to other lithium-ion batteries. It cannot allow a charging or discharging current more than rated value, otherwise there would cause a safety problem.

The batteries that are used in this project are the lithium-cobalt cylinder type batteries, and named as LIR 14500-750, shown in Figure 2.1. Here 14500 means the battery has a height of 50mm and diameter of 14mm, and 750 is the rated charge, namely  $1C = 750\text{mAh}$ . According to the datasheet, the battery has a real size of  $49.8\text{mm}(\pm 2\text{mm})$ 's height and  $14.0\text{mm}(\pm 2\text{mm})$ 's diameter. The typical rated charge is  $750\text{mAh}$  and minimum charge is  $700\text{mAh}$ .

In this thesis, if there is no specific explanation, the description on lithium-ion batteries in the following chapters just indicates the lithium-cobalt type.

Li-cobalt batteries are vastly used in portable devices such as mobile phones, laptops, cameras.



**Figure 2.1.** LIR 14500 batteries that are applied in this project

The lithium-manganese battery uses lithium manganese oxide as the cathode material. It applies a 3-dimension spinal structure then to enhance the ion flowing ability. As a result, the internal resistance is lowered and its ability to handle flowing current is improved. In another word, the lithium-manganese battery is able to conduct a fast, large current on charging and discharging. Furthermore, it has a high temperature stability and good safety. Its drawback is the short life span, as well as the less capacity compared to lithium-cobalt battery.

Lithium-phosphate battery applies the phosphate material for the cathode. This kind of battery has a low internal resistance hence is able to handle a high current. It has a very good safety condition and thermal stability, as well as a long life span. Its weakness is the lower specific energy. Typically its nominal voltage is 3.3V per cell, and compared to 3.7V per cell's nominal voltage of lithium-cobalt battery, it gives out a lower capacity.

Nickel materials can provide a high specific energy while manganese forms a 3-dimension spinal structure thus to lower the internal resistance. Li-NMC batteries just utilize the combination of nickel and manganese on the cathode to supply either a high specific energy or a high specific power. Such lithium-NMC batteries are mainly applied in electrical transportation tools, for instance, the electrical vehicles(EV), electrical bicycles and so on, they can also serve the powertrains as well.

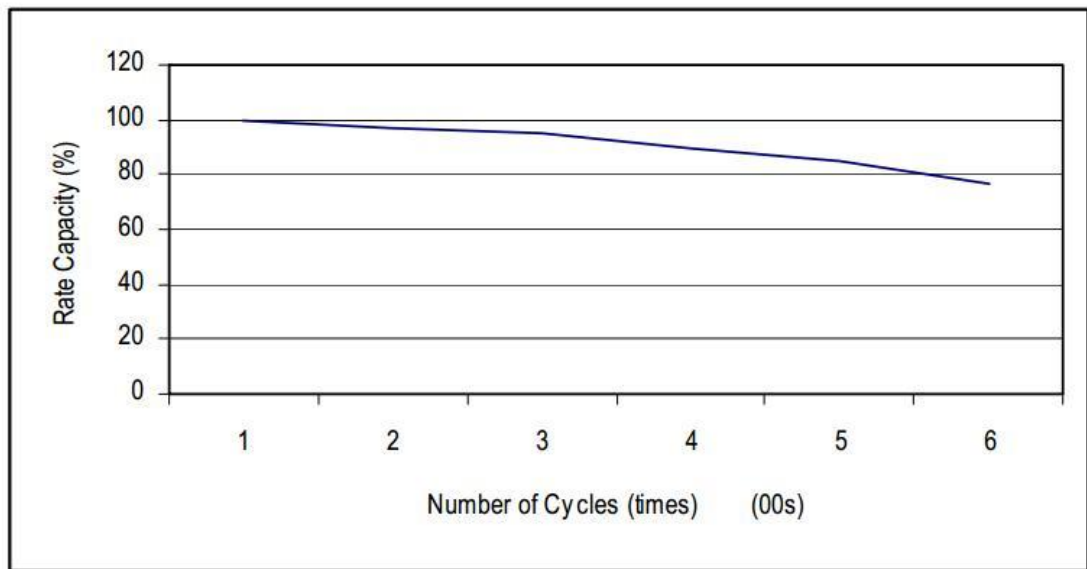
Lithium-NCA batteries have the benefits on their high specific power and power densities, as well as the long life span, but the less safe and high costs are the shortcomings that need to be concerned. This kind of battery is not commonly used in market.

LT batteries use the titanate material at its anode instead of the graphite material for other typical lithium-ion batteries. This type of material forms a spinal structure in order

to improve the ion flowing ability. This kind of battery is able to deliver charging and discharging current as high as 10 times of the rated value. It has a good safety condition and low temperature stability. Besides, it has a longer life span compared to other typical lithium-ion batteries, nevertheless, with a relatively lower specific energy.

### 2.1.2. Lithium-ion battery capacity

Battery capacity is regarded as the key performance indicator, which specifies the energy that a battery can provide in Ampere-hours(Ah)[22]. In general, the C-rate is utilized to rate the discharge(charge) ability in respect to battery capacity. Most batteries are rated at 1C, which means the current that a battery is supposed to provide in one hour in ideal case. For the AA-size lithium-ion battery that is used in this project, its specified full capacity is 1C=750mAh, indicating ideally it is able to provide a current of 750mA in one hour. However, after tens to hundreds of charging and discharging cycling, the capacity would decrease, and results in a reduced lifetime. Figure 2.2 below shows how the LIR14500-750 battery capacity drops gradually along with the numbers of cycles.



**Figure 2.2.** Battery capacity decreases along with the number of cycles[18].

### 2.1.3. Open circuit voltage (OCV) and closed circuit voltage(CCV)

Battery's open circuit voltage (OCV) is also known as the nominal voltage. It is the voltage potential that a battery can produce without being charged or loaded. Battery's open circuit voltage per cell is tightly involved with its state of charge. Generally, a lithium-ion battery has a rated voltage of 3.6V/cell to 3.7V/cell, and a cut-off discharge voltage of 2.75V/cell. The LIR14500 battery utilized in this project provides a nominal voltage of 3.7V/cell, and cut-off discharge voltage of 2.75V/cell, at temperature of 25°C. Here the cut-off discharge voltage means the lowest voltage that one battery cell

could be discharged to. If the cell voltage goes lower than cut-off voltage, it would bring damage to battery.

Table 2.2 presents a comparison of lithium-ion battery with other chemical types of commonly used rechargeable batteries. It can be seen that lithium-ion battery provides the highest nominal voltage, approximately three times of that of NiMH and NiCd battery, and around 1.5 times of that of Lead-acid battery. Hence for a specified supply voltage, fewer cells are needed with lithium-ion battery pack, which is favored for portable devices.

**Table 2.2** *Nominal Cell Voltage of Different Rechargeable Battery Chemistries*

Chemistry	Nominal Cell Voltage(V)
Lead-acid	2.0
Lithium-ion	3.7
NiMH	1.2
NiCd	1.2

However, lithium-ion battery requires an extremely high accuracy on voltage, it can only tolerance an error less than 1% for the sake of safety. For instance, with a cut-off charging voltage of 4.2V, the tolerated error is 0.042V. Cell voltage over this limitation would cause a permanent damage to battery.

Closed circuit voltage (CCV) is the produced voltage when battery is being charging or discharging, or in another word, when battery is placed inside of a closed loop. CCV is in the position of fluctuation all along. It records the dynamic voltages related to the load for batteries.

#### 2.1.4. Charging and discharging lithium-ion batteries

Battery charging is an essential and crucial issue regarding the cycling life and performance of batteries. A proper charging process would keep batteries in a good capability; in contrast, an illegal charging would cause harm or even danger to batteries.

In essence, to charge batteries is to trigger ions to move from anode to cathode and get embedded there. The more ions are embedded in cathode, the more energy capacity is charged in. In particular, charging for lithium-ion batteries needs a more strict and tricky way concerning its inherent characteristics.

There are two stages in charging lithium-ion batteries, constant current (CC) stage and constant voltage (CV) stage[1][15][19]. At the beginning, a battery is charged with a constant current; meanwhile the battery voltage is correspondingly increasing in a relatively sharp slope. As the voltage reaches the full voltage, charging process enters the constant voltage mode, where the charging current decreases and voltage stays stable at its full voltage. This stage is also called the saturation charging stage. When the current drops to the predetermined end current, the battery charging process cedes.

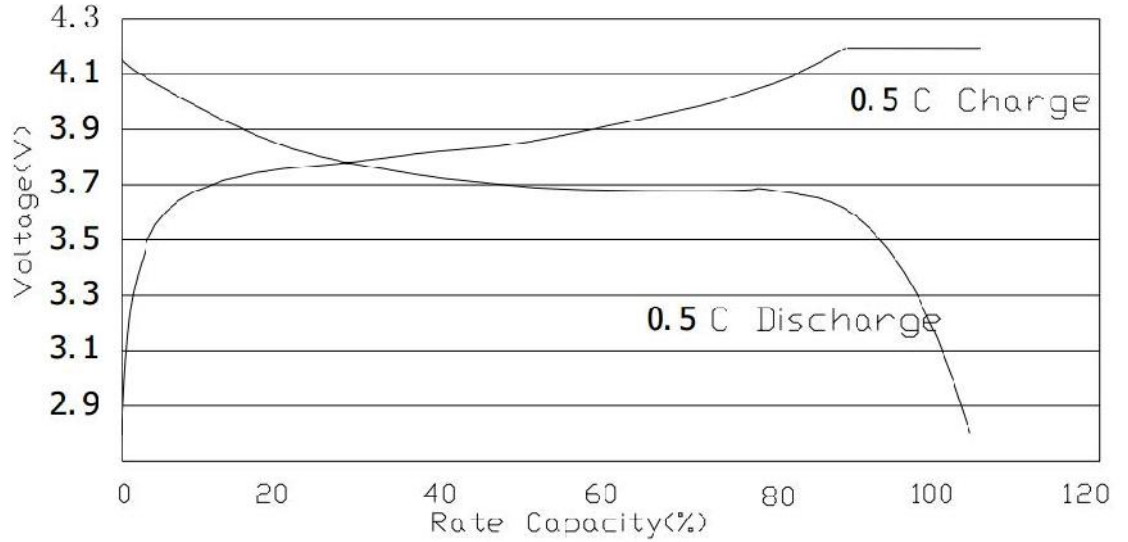
There are different charging methods for lithium-ion batteries according to different charging standards. Basically, they are the standard charging, general charging and apace charging that are commonly used. Standard charging is the charging criterion from manufactory, which gives the least harm to batteries. General charging method applies the allowed current which saves charging time meanwhile ensuring batteries safety. However, compared to standard charging, general charging method shortens batteries use life faster. Apace charging uses high charging current, normally is 5 times of that for standard charging. Normally, it is not preferred to use apace charging method.

For the LIR14500 battery that is used, standard charging requires a constant charge rate of  $0.2C(150mA)$  and constant voltage of  $4.2V$  for these two stages respectively, as well as the end current of  $0.01C(7.5mA)$ . For general charging, it requires a CC of  $0.5C(375mA)$ , CV of  $4.2V$  and end current of  $0.01C$ . And for apace charging, CC of  $1C(750mA)$ , CV of  $4.2V$  and end current of  $0.01C$  are needed.

Generally speaking, apace charging is not recommended. With a high current of  $1C$ , the battery would reach its peak voltage quickly indeed, which however, does not lead to a full charging. As a matter of fact, this even requires a longer saturation stage in order to get a full capacity. Full voltage does not equal to full capacity. This phenomena described in visual effect is just like to quickly pour the beer into a glass and results in emerging lots of bubbles. The glass seems to be full but the actual beer liquid is just a little amount.

Similarly, lithium-ion battery has specific requirements on discharging mode. The maximum discharging current is generally limited at  $2C$ . Larger discharging current would cause a serious thermal damage to battery. Besides, the produced thermal energy is converted from the battery stored energy. The larger the current is, the more thermal energy there would be, which renders a reducing of the battery available capacity.

Both overcharge and over-discharge should be strictly avoided. When a battery cell is fully charged, lithium-ions embedded in anode are totally saturated. If it is still being charged, ions would be preticipated continuously. This would cause series safety problems to the batteries. At the worst case, overcharging would lead to batteries explosion or fire. Therefore, overcharging should be definitely avoided. On the other hand, if a battery cell is still in discharging after it has already reached the cut-off voltage, the remaining energy would be quickly extracted to empty. Then there produce some lithium dendrites, which would cause the battery an internally short circuit. Since now the energy in battery cell is already fully drained, there will not cause danger for users. Nevertheless, this cell has sustained permanent damage, and cannot be used any longer.



**Figure 2.3.** Charging and discharging characteristics of lithium-ion battery[18].

According to the datasheet of LIR14500 battery, the rated discharging current is defined as 0.2C, which equals to 150mA. In order to provide a safe discharging circuit, a suitable load is built up to consume current. Figure 2.3 explains the characteristic curve of LIR14500 battery both on charging and discharging, under the temperature condition of 25°C.

In this battery management system design, Hyperion EOS0606i is applied for battery charging as supplement. Hyperion EOS0606i is an intelligent portable device operating as a battery charger. It supports multiple chemical kinds of batteries and is able to charge a battery pack with up to six cells. Charging current can be set through the control screen on the device. It follows the first constant current and then constant voltage rules for charging. For instance, when the LIR 14500-750 battery is about to charge, first of all, battery type lithium-ion is selected. Then since we wish a charging current of 350mA, this can be set as 0.35 on the control screen. Cell number is labels as 'n'S, which can be set on the control screen as well.

On the other hand, for the discharging load, a stray of light-emitting diodes with resistors in series are used. When there is current flowing through, the LEDs would be lighted on indicating a discharge is operating.

### 2.1.5. State of charge

State of charge (SoC) is quite a straightforward indicator which demonstrates the dynamic remaining charge of a battery in terms of its full capacity, usually rated in percentage. It is defined in formula as[4]

$$SoC[\%] = SoC_{Ef} + \frac{Q_{cbg}}{Q_{max}} \times 100 \quad (1)$$

where  $Q_{cbg}$  is the remaining charge of the rated battery while  $Q_{max}$  is the maximum capacity, and  $SoC_{Ef}$  is the initial SoC before charging. For instance, for a fully charged battery, its SoC is 100%, and a SoC of 0% for a totally discharged battery. State of charge is also a significant parameter to describe the performance of battery.

Since lithium-ion batteries are applied in various fields such as portable devices, electrical vehicles, powertrains and smart grids, it is definitely important and necessary to ensure that the batteries are working in a reliable and safe condition. Also people would like to know whether batteries are able to deliver a required energy. Hence an accurate and timely estimation or calculation on battery state of charge is in need.

Measuring state of charge is intricate and complex since it involves cell voltage, current flow and temperature, as well as other elements. The simplest and most direct way is to estimate state of charge according to the measurement of its open circuit voltage (OCV) based on its self-discharge curve. The measured values are then translated to a SoC look-up table related with OCV.

The most advantage of this method is the simplicity and speediness. The SoC value can be obtained as soon as the batteries are connected to the BMS and the system is executed. However, this method works well on simplicity yet fails on representing an reliable value[4]. Cell remaining capacity is not the only element that determines the SoC, temperature and discharging rate are also two important factors to be concerned. With different temperatures and discharging rates, the cell displays different self-discharge curves. Besides, as seen from Figure 2.3., except for the fully charged and discharged sections, most of the part is depicted as a flat curve. A slightly floating voltage renders a distinct variation on state of charge. The characteristics of SoC versus voltage do not present a linear curve, hence SoC estimation based on this exits large error.

In spite of such weakness as imprecision, voltage-based method is still widely used for its simplicity, if the accurate SoC is not strictly required. In this project, the SoC of each single cell as well as the whole battery pack are estimated by dynamic cell voltage in real time. Besides, a more accurate method based on current flow is proposed and would be more into studied in the future.

Nowadays there are plenty of methods on accurate SoC estimation. Research on an accurate SoC estimation is also one important part of future study. [2] introduces a SoC estimation by electrochemical impedance spectroscopy measurements based on fuzzy logic system, this method gives a very accurate approach yet a complex implementation. [3] uses a resistor-capacitor(RC) equivalent model to enhance the accuracy of SoC estimation based on battery open circuit voltage(OCV), with the assumption that the OCV-SoC curve is piecewise linear. [16] gives a linear parameter varying (LPV) method to lower the complexity of Kalman filter meanwhile providing a good accuracy.

Generally, for the BMS devices which provide the function to calculate the SoC for batteries, it is usually the Ah calculation method based on battery current that is most

commonly used one. It gives a relatively high accuracy on SoC with simple configuration and algorithms, which would lower the cost of devices.

### 2.1.6. State of health

State of health (SoH) is the indicator of battery aging effects[2][7]. Basically, state of health is evaluated by the reducing of battery capacity, which is the intuitive and primary result of battery aging. By evaluating the SoH of current situation, the future performance of a battery cell can be predicted, as well as the remaining useful lifetime. State of health is defined as the relation between the actual available battery capacity with nominal battery capacity that

$$SoH = \frac{C_a}{C_N} \times 100\% \quad (2)$$

where  $C_a$  is the actual available battery capacity and  $C_N$  is the nominal battery capacity. It is determined by several different battery parameters, such as internal resistance, self-discharge, charge acceptance and chemical changes[7]. Users can define a threshold value of SoH for batteries according to the datasheet. The state of health begins to drop in accordance with the deterioration of the battery cell's performance. When its SoH drops below the threshold value, this battery cell reaches the end of its use life.

## 2.2. Battery balance technology

In order to provide enough output voltage to power up the external devices, generally a battery pack that is made up with multiple batteries connected in series is utilized. In this way, the total supply voltage is just the sum of voltage of each battery cell. Nowadays, such construction with serial battery cells is widely applied in quite a few fields, such as base station, electrical vehicle, and UPS, etc. In series connection, the current flowing through the pack are the same for every single cell for either charging or discharging. However, the performance of all battery cells cannot be identical. There always exist more or less practical differences, such as internal resistance, internal chemical variations, numbers of cycling, temperature effects and so on[9][13]. Therefore, it is possible that battery imbalance problem comes up among multiple cells, and it would lead to critical problems on battery performance.

For instance, for a 12-cell battery pack which supplies a voltage of 48V, in ideal case, each cell should provide an identical voltage of 4V. Nevertheless, due to the imperfection of manufacturing process and environmental effects, these cells can never be so exactly the same. Normally, for a well-balanced pack, the difference of the capacity among cells does not exceed 3%.



### 2.2.1. Problems of battery imbalance

When the battery pack is working in an imbalance status, the weakest cell(s) would determine the pack's capacity and performance. This is just like the Cannikin law, the shortest board decides the amount of wine that a cast can hold. Under the imbalance situation, the battery pack would be neither fully charged nor completely discharged to either of the cut-off voltages. As a result, the available capacity would be deducted as well.

Specifically, during the constant current charging process, when the weakest cell(s) have already reached the predetermined cut-off voltage, other cells still require charging. In order to prevent overcharge to one single cell, the whole pack would turn into constant voltage charging mode while the total pack's voltage is actually lower than it's supposed to be. Besides, during constant voltage mode, the weakest cell(s) would cause the charging current to drop in an accelerated rate other than the normal cells. Therefore, under the imbalance condition, the whole battery pack would suspend charging without obtaining a full capacity.

Similarly, during discharging the weakest cell(s) would extract energy to the cut-off voltage faster than other cells. Then discharging would cease in case of permanent damage to battery cells, whereas other cells are indeed available to deliver more energy. In this case, the discharging process would end up with reduced energy utilization efficiency and a shortened runtime. Thus it can be seen, even with only one single imbalance cell, the performance of whole battery pack would be seriously restricted.

Battery balancing is the vital and critical technology in battery management system. It helps to improve the capacity as well as to enhance the energy utilization efficiency of the whole serial battery pack, so as to prolong the battery lifetime.

### 2.2.2. Battery balancing method

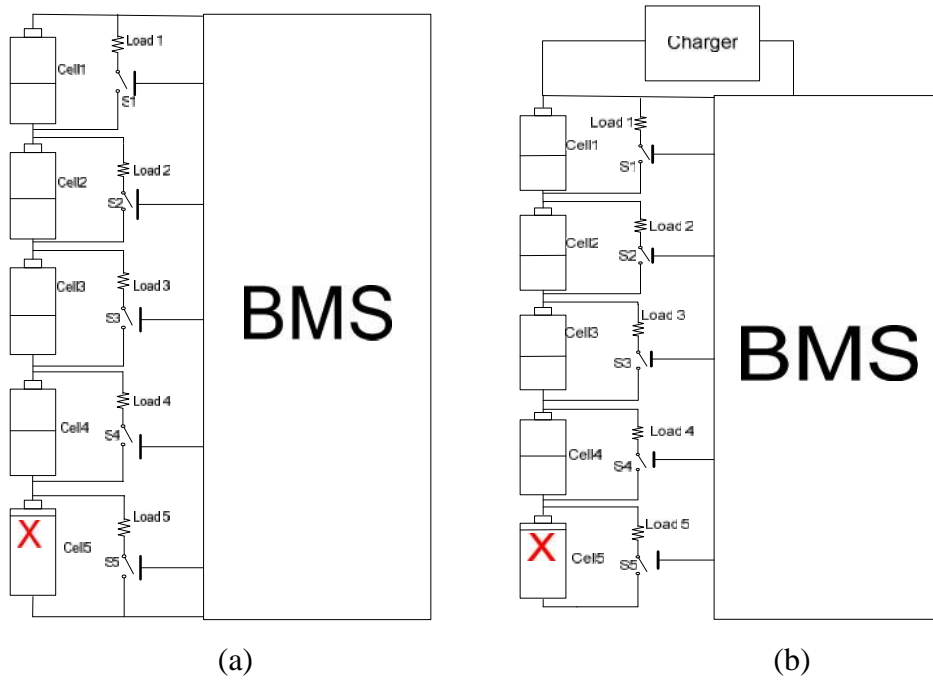
Battery balancing is the most important task of battery management system, and it is classified by passive and active balancing. Topologies for different balancing methods are concluded in Figure 2.6.

Passive balancing is achieved by bypassing the current of battery cell with resistors until the charge of each cell is matched. In this balancing topology, a passive, current-limiting resistor is shunt with each battery cell for controlling[10]. When there detects imbalance on pack, the shunt resistor is activated as an extra load to bypass a current flow. In this way, the energy is released and wasted as heat[11].

The passive balancing method is classified as fixed mode and switch mode. For the fixed mode, the shunt resistors are activated all the time bypassing the current which is then dissipated as heat. This topology is simple and low cost but wastes energy and not efficient. It is available for Nickel and Lead-acid batteries which allow the overcharge [11].

In the switch mode the bypassing shunt resistors are activated by the controlling switches. The resistors will remove the extra charge from the higher charged cells. For

instance, during the charging process, the battery cell with a relatively poorer performance would reach higher voltage quickly than others. When an imbalance is detected, the charging process is then paused for a while, and the resistors on the weaker cells' branches are shunt by switches, leaving these cells to discharge until their cell voltages match with others. Then the battery stack continues charging process. Once there discovered an imbalance, the steps discussed above would be repeated until all the cells are fully charged to their maximum capacity. This topology gives a more efficient battery balancing and can be used for lithium-ion batteries. Figure 2.4 depicts a detailed example explaining how the switch mode performs balancing.



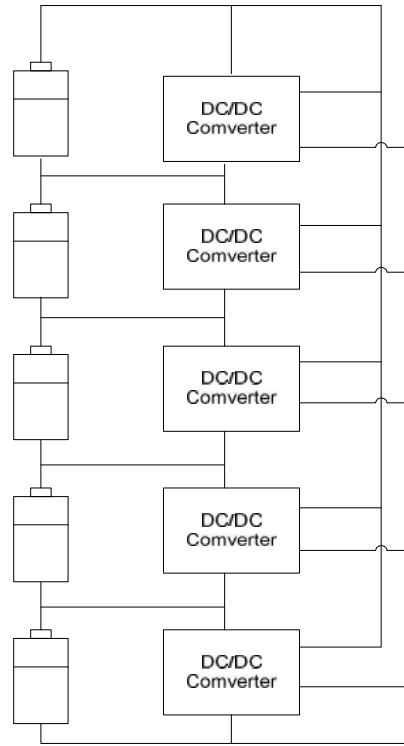
**Figure 2.4.** Passive battery balance topology for switch mode

As shown in Figure 2.4 (a), cell 5 is detected with much higher capacity compared with other cells, then the switch S5 connected with it be switched on externally by user. Load 5 will consume the extra battery energy until the S5 is switched off by user, meanwhile the BMS monitoring the charge situation in real time so as to give a feedback on battery pack balance performance. Similarly, during the charging process, battery balance is also concerned. As shown in Figure (b), cell 5 is detected to be charged faster than others, then charging is paused and cell 5 is left discharged until it is matched with others.

The main merits of passive balancing method are the simplicity and low cost. However, as the shunt resistors work as removing the extra charges which are then dissipated as heat, both of the two modes discussed above have the energy efficiency problem.

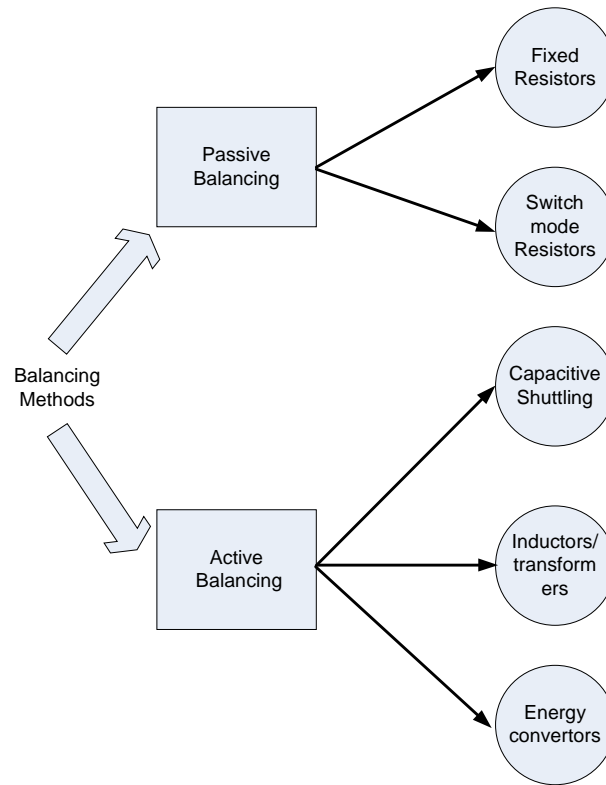
Active balancing, on the contrary, achieves batteries balancing by energy distribution. They are the balancing cells or integrated circuits that are applied and the energy is redistributed among the cells other than being wasted. Specifically, the system monitors

the charge condition for each single cell and draws energy from the most charged cells to compensate the least charged ones[12]. Hence in this way, active balancing provides high energy utilization efficiency.



**Figure 2.5.** Active battery balance topology

Active balancing method is categorized as several modes depending on the components that are utilized[11]. The capacitive shuttling method uses capacitors to shuttle the energy among the battery cells in pack. This method provides with simple configuration and low cost, but fails at balancing speed. Similarly, inductors or transformer are applied to redistribute energy among cells in inductor/transformer balancing method, which satisfies a high balancing speed and high energy conversion efficiency. But this method needs external capacitors in high switching frequency. In energy converters balancing method, integrated converters such as buck boost converter, flyback converter, and other converters are utilized. Figure 2.5 gives a simple topology of such method. Converters balancing method is able to fully achieve energy conversion and control process in high efficiency and fast speed, however, the complexity and high cost is its main disadvantage.



**Figure2.6.** Topology of battery balancing methods [11]

**Table 2.3.** Comparison of different balancing methods

Balancing methods		Advantages	Disadvantages
<b>Passive balancing</b>	Fixed resistors	Simple to implement, achievable in small size	Low efficiency, high power loss
	Resistors with switches	Simple to implement, achievable in quick balancing	Low efficiency, high power loss, resistors able to handle high power needed, external circuitry needed
<b>Active balancing</b>	Capacitive shuttling	Available for both charging and discharging mode	Batteries balancing rate is not high enough, external circuitry needed, complex control for some configuration
	Inductors/transformers	Fast batteries balancing rate	Complex control, expensive configuration
	Energy Convertors	High efficiency, fast balancing rate, widely application	Complex control and implementation, expensive configuration

In this project the BMS, LTC6803-2 that is utilized, adopts the switch mode passive balancing technology to achieve the battery pack balancing[16]. There are 12 MOSFET switches connected with battery stack, each for one battery cell. When one cell of the stack is detected to be imbalance with others, users can control the BMS to switch on discharge mode to bypass its current so as to release the extra energy.

## **3. BATTERY MANAGEMENT SYSTEM**

### **3.1. Introduction on BMS**

Battery management system (BMS) is the integrated module used to manage batteries in order to maintain a stable and health operation status. In the use of rechargeable batteries, the issues that should be concerned the most are the overcharging and over-discharging, which would lead to damage and lifespan reducing or even explosion and fire to batteries. Therefore, when using rechargeable batteries, BMS is always a must to protect the batteries, both from performance and safety. Connected with the battery pack, BMS then can detect the battery voltages, currents, and temperatures. Meanwhile, it manages the thermal control, battery balancing, remaining capacity calculations and SoC and SoH report.

The main functions of BMS can be summarized as the following points specifically.

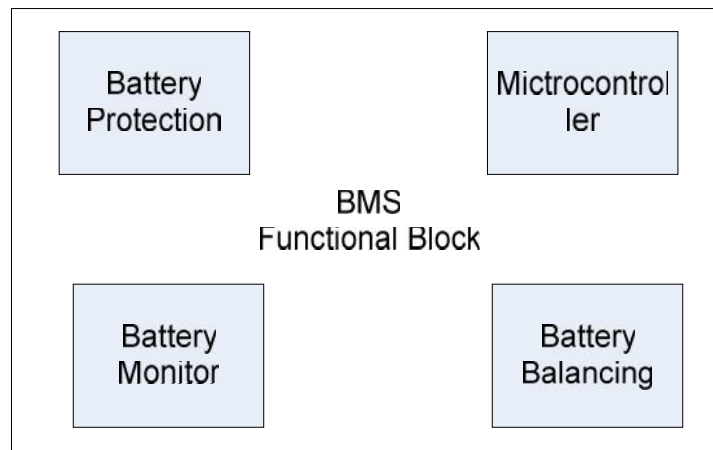
- SoC estimation
- Battery cells measurement
- Battery balancing
- Battery performance report to users

Specifically, BMS would correctly estimate the state of charge (SoC) of battery cells, so as to ensure the SoC is within the reasonable range, thus preventing the damage to battery cells due to overcharging or over-discharging. It can also accurately measure the cell voltage, temperature and charging/discharging current in real time, as well as the total voltage of a battery pack. Also to detect the state of health (SoH) of battery cells in real time, in order to ensure the whole pack of battery cells are working safely and reliably. Furthermore, one BMS is able to balance batteries between each individual cell within the whole pack, hence to enhance the performance of series battery pack and prolong the service life of each cell. Finally, BMS is responsible to report the battery status detected above to the users promptly, in order to let the users to make decision on batteries.

Generally, the BMS manages batteries status and performance, but the external blocks such as the load or charger are not included. It only provides a communication port to those external circuitries, with available communication data and status report. However, with further modifications by users, the BMS is capable to provide the function to control such external circuitries.

The basic functional blocks of a BMS are shown in Figure 3.1. The battery protection block includes the charging/discharging protection and over-current protection. BMS detects the batteries operating voltage and current. Once the voltage or current goes be-

yond the rated value, BMS stops working and enters into protection mode, meanwhile alerts a warning to users. The battery monitor block can be also regarded as the data collection block, where the voltage signal, current signal and temperature signal are detected and collected, and then given as a feedback to the display unit. Considering the system reliability and the cost, it is better to keep BMS signal collection block as simple as possible. More signals to be detected leads to a more complexity, which is not preferred. Microcontroller block provides the data communication ports and accomplishes data exchange with host controller. The battery balancing block provides a feature of battery capacity equalization. Similarly, BMS detects the batteries capacity based on voltage and current, and balances them by passive method or active method. Besides, some BMS are also configured with the SoC calculation block, which utilizes the collected voltage, current and temperature signals to estimate the state of charge of batteries, and then transfer the results to the display unit.



**Figure 3.1.** Battery management system (BMS) mainly functional blocks

### 3.2. Battery monitor stack LTC6803-2

In this project, a multicell battery stack monitor LTC6803-2 from Linear Technology is adopted as BMS. LTC6803 is a data acquisition integrated circuit, one demonstration board is able to measure up to 12 series connected battery cells, and it supports different kinds of chemical material of batteries as well as supercapacitors[17]. It is fabricated with individually addressable serial interface, which allows up to 16 devices to interface with one micro controller and operate simultaneously. This BMS also allows an isolated power supply. By powered up by isolated supply, it does not need to drive power from batteries or supercapacitors stacked in, and can be easily powered on or off. Working as a battery monitor, it is able to provide the measurement results with 0.25% maximum total error. Considering such features of LTC 6803 device, it is widely applied on electric and hybrid electric vehicles, bicycles and motorcycles, as well as other high power portable equipments.

There are multiple different devices in series LTC6803. The main functions provided are quite the same among them. The differences are the interface and pin connections.

LTC 6803-1/3 applies serial interface daisy chains to adjacent devices, while LTC 6803-2/4 using individually addressable serial interface. Specifically, LTC 6803-1/2 connects bottom pin with  $V^-$  internally, whereas LTC 6803-3/4 separates these two pins. The former one provides a drop-in upgrade, and the latter way improves the accuracy of measurement value on cell 1.

In this project, series LTC 6803-2 is utilized. With individually addressable serial interface, it gives a more freedom in programming on multiple devices connection. Also it provides a drop-in upgrade with the connection of bottom stack with  $V^-$ .

### 3.2.1. IC module function blocks and operation

- **Functional Blocks**

LTC 6803-2 IC module is made up of a 12-bit delta-sigma analogue-to-digital converter (ADC), input multiplexer, voltage reference, balancing circuitry, watchdog timer, and configuration register.

The multiplexer is connected between battery stack with 12-bit ADC. The voltage reference is used to provide with a distinctively accurate measurement. The balancing circuitry is configured by internal MOSFETs, which are applied to discharge batteries or control external balancing circuits. After the measurement command is set, the device would indicate an ADC status. The converter reads the measurement results and gives an output code with 12 bits. The specific applications of ADC will be explained later in the *Operation* section.

LTC 6803-2 supports a passive balancing. When the battery cells are discovered to be over charged, the MOSFET switches are turned on to discharge the redundant charge. However, the device itself does not determine whether to switch on or off the MOSFETs for batteries balancing; it is the user through host processor to make the decision. The configuration register is used for the command set from host processor to control the balancing switches. If some interruptions occur during communication between host processor and register, the watchdog timer is utilized to detect and turn off the discharge switches.

Reference module is applied for providing the measurement results with high-accuracy. And the DIE TEMP module is for cell temperature measurement. LTC 6803-2 provides temperature sensor inputs. A simple external thermistor combined with resistor can be connected to the board. Temperature is measured as a format of voltage with respect to the most negative potential and then stored in TMP register.

- **Operation**

SPI compatible serial interface is applied for the device LTC 6803-2 to communicate with host processor, which allows multiple devices to interface with one processor. Each of the devices is identified with one specified address defined by users.

The LTC 6803-2 internally connects the bottom of the stack, which indicates battery stack the most negative potential point, to  $V^-$ , giving a drop-in upgrade.



There are three modes of operation of the device: hardware shutdown, standby and measurement. For hardware shutdown mode, there is no power supply and the standby mode is for power saving, all the circuits turn off and only the serial interface is still operating. On measurement mode, the device measures the cell voltages and temperature, and then gives the measurement results back to users for the cell performance judging.

During the measurement, ADC gives a 12-bit output. For the absolute value 0V, its corresponding code is 0x200, and -0.768V for code 0x000. The absolute ADC operating range is from -0.768V to 5.376V, with code from 0x000 to 01000, and the actual useful range is -0.3V to 5V. Meanwhile, the balancing discharge MOSFET switches will automatically turn off when a measurement command is set out.

The LTC 6803-2 has two general purpose digital input/output pins(GPIO). When a GPIO configuration bit is written to a logic low, it activates the open-drain output. Then the circuitry around can be controlled switched on or off by users. On the other way, if one pin is written to logic high, the GPIO pin can be used as input.

The SPI bus compatible serial port is applied for the device to communicate with host processor, through which multiple devices can be interfaced with in parallel. The address pins for indicating each device are A0, A1, A2 and A3. There are four pins, CSBI, SCKI, SDI and SDO that physically make up the serial interface.

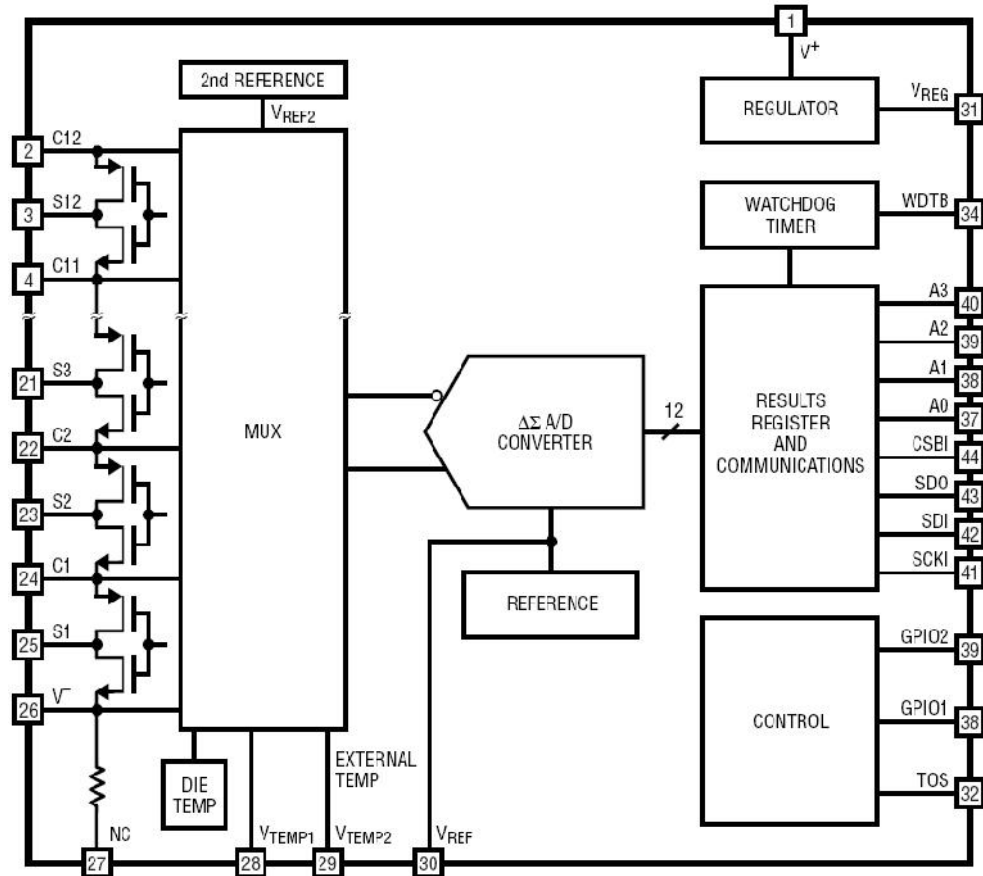


Figure 3.2. Block diagram of LTC 6803-2 IC module [17].

The block diagram in Figure 3.2 displays every specific functional module and their corresponding pins.

Pin 1 ( $V^+$ ) is the positive power supply point, connected to either the most positive potential of battery pack or the external power supply. It can also be used as the isolated power supply potential.

Pin 2,4,6,8,10,12,14,16,18,20,22,24(C1~C12) are the input points of battery cells' or supercapacitors' voltages.

Pin 26( $V^-$ ) is the most negative potential, which is connected with the most negative terminal of the battery pack.

Pin3,5,7,9,11,13,15,17,19,21,23,25(S1~S12) are the pins for balancing the battery cells. Each of them is connected with an internal MOSFET. If one battery cell is detected to be overcharged, the users set out an output signal through the pin, which switches on the MOSFET and enables the discharging.

Pin 27, 33(NC) are internally connected to Pin 26 and not used.

Pin 28, 29( $V_{TEMP1}$ ,  $V_{TEMP2}$ ) are used as temperature sensor input, which monitor the cell temperature from the thermistor and store the results in TMP register.

Pin 30( $V_{REF}$ ) gives an output of 3.065V's voltage reference.

Pin 31( $V_{REG}$ ) is the linear voltage regulator output.

Pin 32 (TOS) indicates the top of stack input pin.

Pin 34(WDTB) is the watchdog timer output.

Pin 35, 36(GPIO1,2) are the general purpose digital input/output pins. When a GPIO configuration bit is written to logic '0', it activates the open-drain output. If one pin is written to logic '1', the GPIO pin is high impedance.

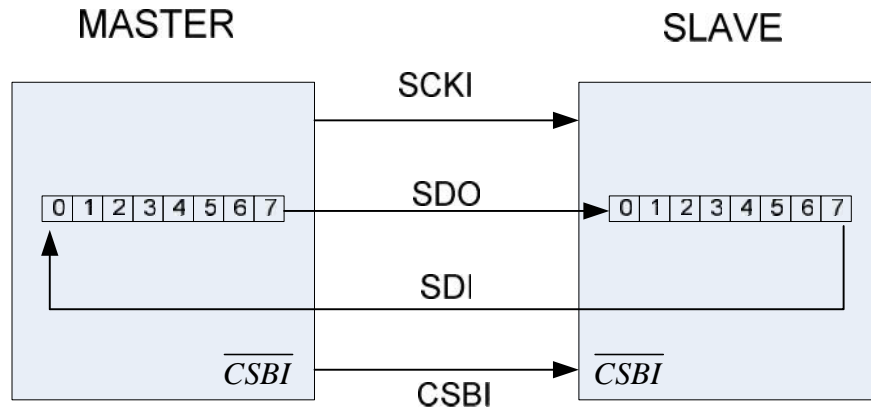
Pin 37, 38, 39, 40(A0, A1, A2, A3) are the address pins, which are used to set the address of each individual device connected to the host processor.

Pin 41, 42, 43, 44 (SCKI, SDI, SDO, CSBI) are the serial input pins, implementing the communication with host PC.

### 3.2.2. Serial peripheral interface (SPI)

SPI communication is applied for the device LTC 6803-2 to communicate with host PC. The serial peripheral interface bus operates as a serial data link. It communicates in bi-direction port, namely, full duplex mode. The device using SPI bus transmits data in master/slave mode, and the data frame is initiated by master device.

This serial interface bus is comprised by four pins, they are CSBI, SCKI, SDI and SDO. CSBI is the slave select pin, output by master device, and is set as low position when activated. SCKI is the serial clock pin which is also output by master device. SDI is the master input and slave output pin whereas SDO is the master output and slave input pin. On physical layer of LTC 6803-2 these four pins are on the positions of Pin 41 to Pin 44.



**Figure 3.3.** SPI data sequence transmission

To start a data transmission, the clock signal at SCKI line should be configured at the beginning. The clock signal is set as a predefined frequency. For instance, as toggle polling method for LTC 6803-2 UV/OV interruption is operating, the output signal is set as 1kHz. Specifically, LTC 6803-2 SPI data link is configured to keep SDI stable when SCKI is at the rising edge.

Then master device would give an output of logic low on CSBI line to slave device, and this signal should keep logic low during the entire data sequence transmission. For a single slave device is connected in, the data transmitting starts when slave select pin CSBI signal transits from high to low. If multiple slave devices are used, then each of them requires an individual slave select pin control. For multiple used slave devices, the signal at CSBI line keeps in high impedance 'Z' position if not selected. When a write command is set, the data is then latched at the rising edge of CSBI line.

The data sequence transmission is in a full duplex mode. Each of master device and slave device possesses with an eight-bit register. Then the byte in the register would shift out corresponding to the clock. Data are shifted with most significant bit (MSB) first. When one MSB is transferred, a new least significant bit would shift into the register. For device LTC 6803-2, during write mode, the data sequence in SDI line shift into master's register during the rising edge of clock. Whereas on read mode, data sequence on SDO line is transmitted at the falling edge of clock SCKI.

For the multiple slave devices application, if there are some slave devices that are not used at the moment, its slave selected pin CSBI is then inactivated. The data sequence on the SCKI and SDO line will not be accepted and its SDI line should keep in inactive as well.

However, for the other versions, LTC6803-1 and LTC 6803-3, it is the serial interface daisy chain to be used communicated with adjacent devices.

### 3.2.3. Advantages of LTC 6803-2

Maxim technology provides similar battery management system in market, which supports the comparable function on monitoring battery cells and graphic user interface(GUI). It can also measure different battery chemistries such as Li-ions, NiMH from

6V to 72V, up to 12 cells. It can provide multiple demonstration boards connected in series for monitoring battery more than 12 cells.

Among Maxim family, MAX11068 is the equivalent BMS compared with LTC 6803-2. Either of them has its unique feature that is preferred by different users. Subsequently, there are some particular and unique advantages of LTC 6803-2 over MAX11068, concluded as below.

- Isolated power supply  
LTC 6803-2 supports an isolated power supply, input driven from pin  $V^+$ . With isolated power supply, the board can be easily powered on and off by switching on and off pin  $V^+$ . Besides, the board does not need to drive power from energy pack, which especially provides an operation platform for supercapacitor. Different from batteries, supercapacitors would drain power in a much more speedy way when loaded. Since low capacity would cause damage to supercapacitors, and it is difficult to control the capacity in available range, it is safe and preferred to power up the board by an external power. Therefore, an isolated power supply is necessary for supercapacitors monitor.
- Supercapacitor support function  
With the function of isolated power supply, supercapacitors monitor function is available.
- Smaller electrical board size  
LTC 6803-2 has a smaller size of its demonstration board, which is more portable than Maxim.
- Multiple boards connection  
LTC 6803-2 provides multiple boards connections both in series and parallel ways. It applies the daisy chain SPI communication to each board on a stack and each board can be manually controlled with identical pin address.

### 3.2.4. Demo board application

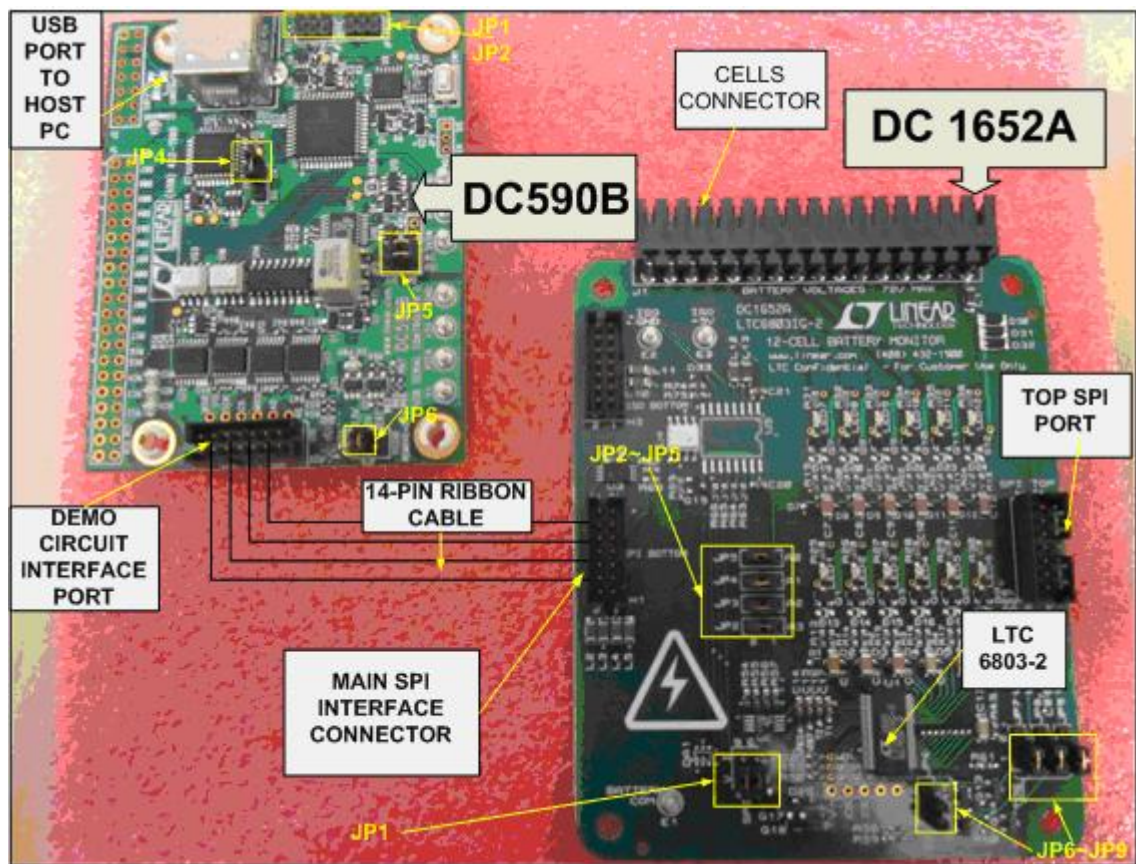
Even the IC module of LTC 6803-2 provides all functionalities as a battery management system, there are external auxiliary circuitries in need to accomplish the functionalities demonstration. Demo board DC1652A is an evaluation circuit to demonstrate the features of LTC 6803-2 integrated circuit as a battery monitor electrical board, and DC590B is an USB-based controlling demo board to match battery monitor board with the host PC. Their configuration and connection in real board are displayed in Figure 3.4.

- Demo board DC 1652A

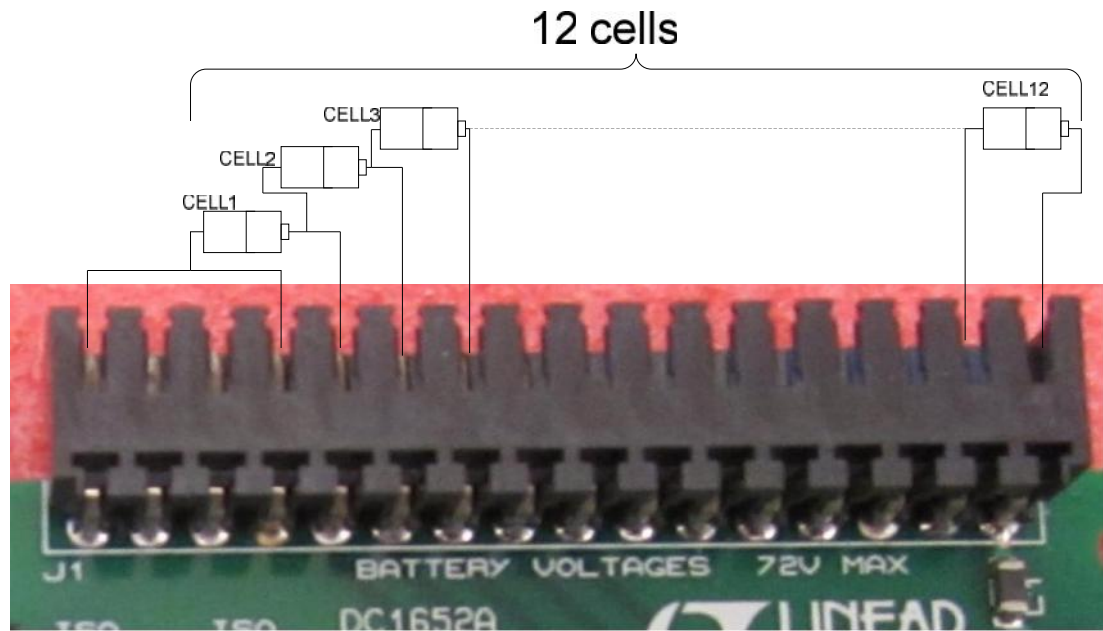
Each single board of DC 1652A can support 12 battery cells in series and the total measured stack voltage is 10V in minimum and 60V in maximum[21]. It possesses with a graphic user interface to demonstrate all its functionalities and provide an access for users to make the control. Theoretically LTC 6803-2 system is supposed to interface up

to 16 boards. However, the GUI provided by product default can only support 10 boards maximum, and each board is assigned with a unique 4-bit addressable serial interface code. On the GUI, a user is allowed to command voltage measurement on single battery cell or the whole battery stack, as well as temperature measurement. For the sake of balancing the battery stack, user can also control the discharging function on individual battery cell or the whole pack as well.

The SPI interface port signed as ‘SPI BOTTOM’ is the main SPI interface connector, through which demo board DC 1652A is interfaced into controlling board DC 590B or other higher level hierarchy boards. The jumpers on board manage different function, and their settings are quite critical.



*Figure 3.4. Demo board configuration*



**Figure 3.5.** 12-cell battery pack connection to LTC 6803-2

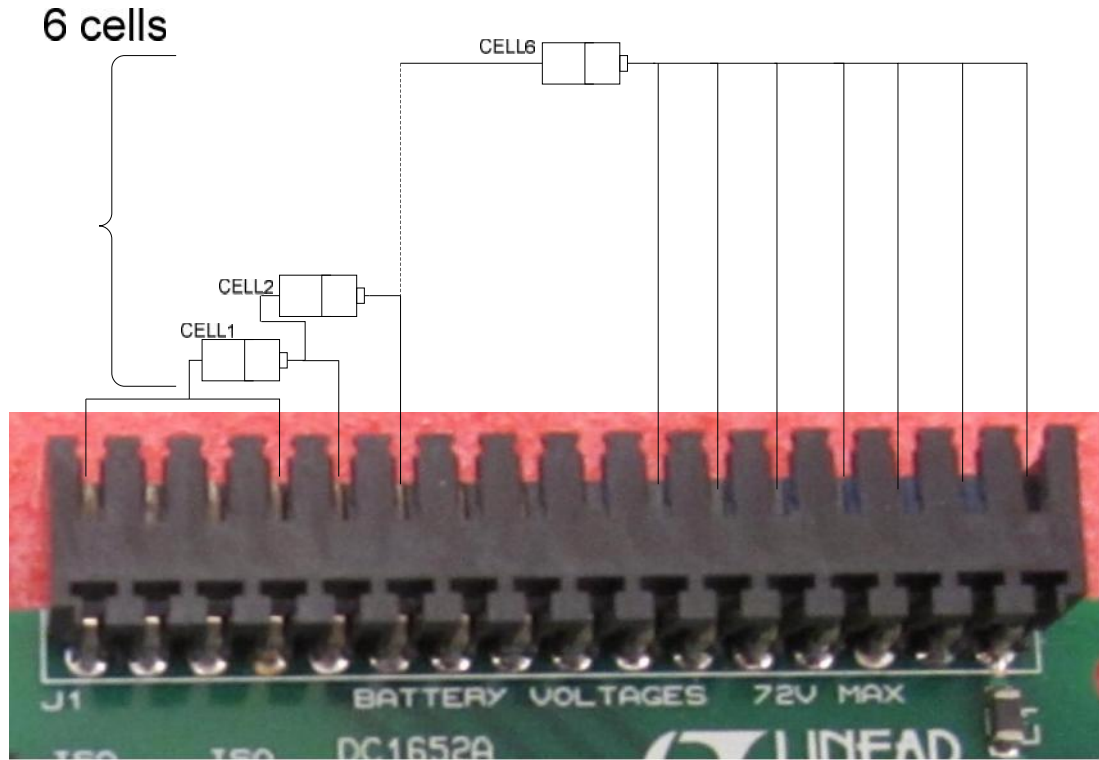
JP1 has two jumper blocks to set the indicating board operating under the voltage mode or current mode, and this jumper is marked as ‘V’ mode and ‘I’ mode. ‘V’ mode is set for the bottom board SPI communication, whereas ‘I’ mode is for both top and bottom daisy-chain communication.

JP2 to JP5 indicate the addressable serial interface, from 0000 to 1111. J2 is the set with one unique code by JP2 to JP5. Then when the whole system is operating, by selecting its individual SPI address on GUI, the demo board can be found.

JP6 to JP 9 comprise the SPI daisy chain. All four jumpers should be moved together, namely, either 0000 or 1111. If JP1 is set as ‘V’ mode, all JP6 to JP9 are set on 1 position, and same for the other way around.

The batteries are connected through cells connector J1. Demo board is designed to measure battery cells from four to twelve. The batteries are connected to an external wiring harness through setscrew, which is then plugged into J1. J1-1 and J1-4 are terminals for ground reference point which should be connected together. Battery cell are connected from J1-4 to J1-16 in between. For instance, the bottom cell, Cell 1, is connected between terminals J1-4 and J1-5, with negative point to J1-4 and positive point to J1-5, and so forth for other cells in sequence. Figure 3.5 illustrates the configuration of battery pack connection. However, if less than twelve cells are connected in, similarly, the bottom cell is connected between terminals J1-4 and J1-5 and with other cells connected in sequence, then the terminals with higher number that are left unconnected should be shorted together. Figure 3.6 illustrates this configuration.





**Figure 3.6.** Battery pack less than 12 cells connection to LTC 6803-2

- Demo board DC590B

Demo board DC590B is basically used for controlling the demonstration boards of Linear Technology's family. These evaluation boards are isolated from host PC and generally not powered up from external source. DC590B board then works for detection on whether these evaluation boards are connected in and their graphic user interface display on screen. The connection between DC590B board and evaluation board is through a 14-pin ribbon cable. The connector is labelled as J4.

Before running controlling board, a software QuikEval should be downloaded and installed well. This software is used to initialize the USB port to SPI communication. USB port does not only transmit control data from host PC to boards but provides an available power as well.

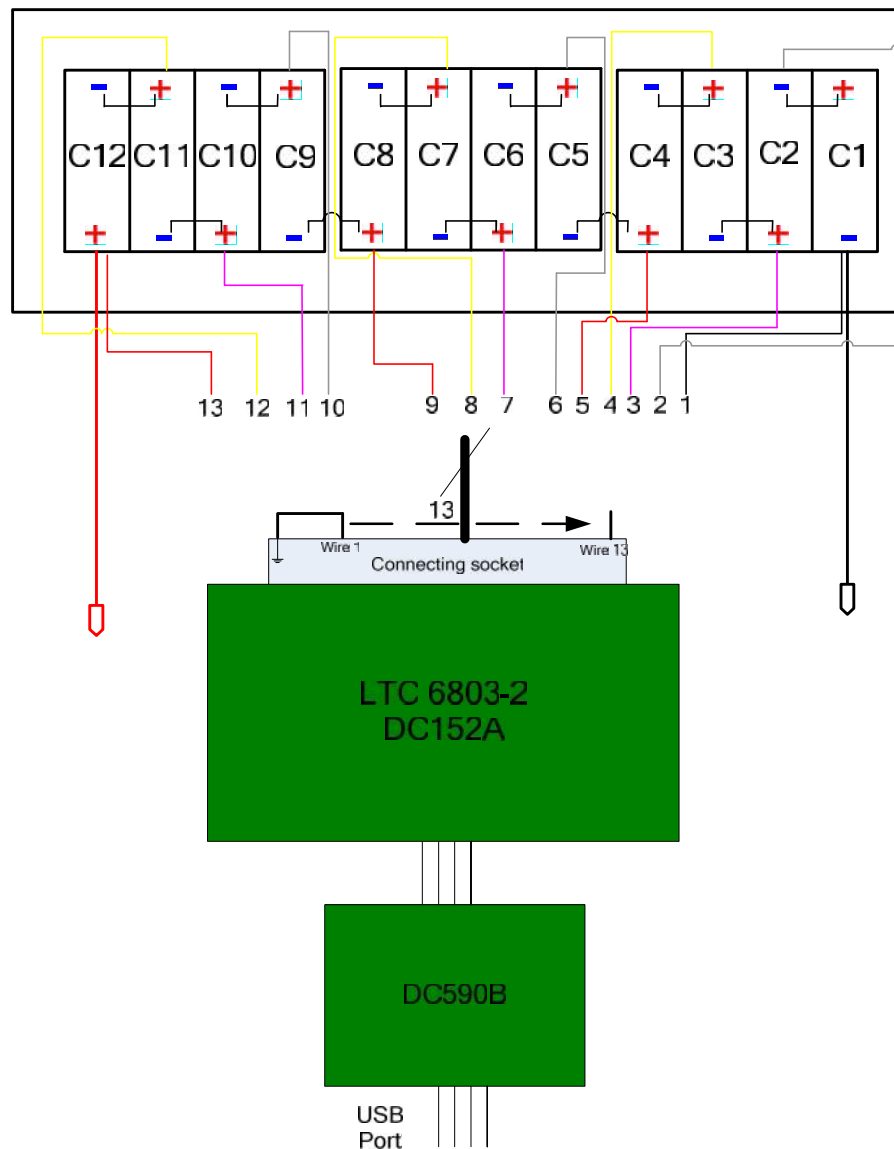
DC590B and the connected evaluation boards can also be powered up by an isolated power supply, one jumper labelled as JP5 with two blocks are used to setup. The block labelled as 'SW' on the right-hand side must be set as 'ON' position, while the other block labelled as 'ISO' controls the isolated power supply.

JP6 is for the VCCA control, which is used to determine the digital signal interface. It can be read on the board that there are three positions for VCCA regulator jumper to be set, they are 3.3V, 5V and EXT. By selecting EXT position, the regulator is shutdown, and an external digital supply must be applied. If the jumper is removed and left open, the regulator is selected as 2.7V.

Besides, such jumpers as JP1, JP2 and JP3 are just left open without any connections. JP4 which is signed as 'EE' must be set as 'EN' position to enable the function.

There are two LED indicators shown up for instructions, ISO PWR LED and COMMAND LED. When the boards are successfully powered up, ISO PWR LED on DC 590B will be lit indicating the onboard supply power is available. Then if there are further commands through USB from host PC sent to the board and waiting to be executed, the COMMAND LED will flicker. In case of quite short duty cycle, this LED flickering may not be apparent.

### 3.3. BMS Configuration



**Figure 3.7.** Functional diagram of the system

The BMS hardware configuration is made up with a 12-cell 3.7V lithium-ion battery pack and DEMO board of LTC 6803-2(DC1652A with DC590B). The battery pack is

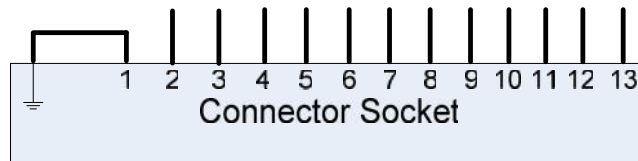


constructed with 12 battery cells connected in series in order to be able to provide a 48V's output voltage. The block diagram of the system structure is shown in Figure 3.7.

### 3.3.1. Battery pack configuration and mapping

The battery cells are configured in numerical order. Starting from cell1, the cathode of the next cell is connected to the anode of previous one. Hence the cathode of cell number 1 becomes the most negative point while the anode of cell number 12 is the most positive point. Two probes draw from both points, with red for the positive and black for the negative, are used for the measurement and charging for the entire battery pack.

Besides the two probes, there are 13 colourful wires with colours stagger from each other. Particularly, the most positive point is assigned with red wire whereas the most negative point is with the black one. There is no specialized colour requirement for other wires, only to intersect the same colours between each other. Each of the wires is extracted from one single node of battery cell and plugged into the socket in sequence. The wire extracted from most positive node is plugged into the most right terminal, and the one for the most negative node is in the forth terminal on the left, which is connected with the most left hole, and so forth for the other wires. The second and third terminals on the left are just left unconnected with anything. All the wires are demanded to be lined out above the board and get fixed.



**Figure 3.8.** Connector socket mapping configuration

This connector socket is just mapping with cell connector on LTC 6803-2 demo board. The most left terminal is mapped to J1-1 and the forth terminal connected with wire 1 is mapped to J1-4 on LTC 6803-2 demo board. Both of them are the ground reference point. All the terminals connected so forth with these 13 wires are mapped to J1-4 to J1-16 for the battery connection on stack. Figure 3.8 above displays the configuration of connector socket mapping configuration.

### 3.3.2. Demo boards setup

In this project, only one battery pack is connected to the board. According to such configuration and the jumper functions description from the datasheet the jumpers on board DC1652A are set as below.

- JP1: Tow jumper blocks are set as voltage mode. The board is set a bottom.
- JP2, JP3, JP4, JP5: Jumpers are set together to position '0'. Board address is set as 0000(The board communication address can be selected as arbitrary from 0000 to 1111).

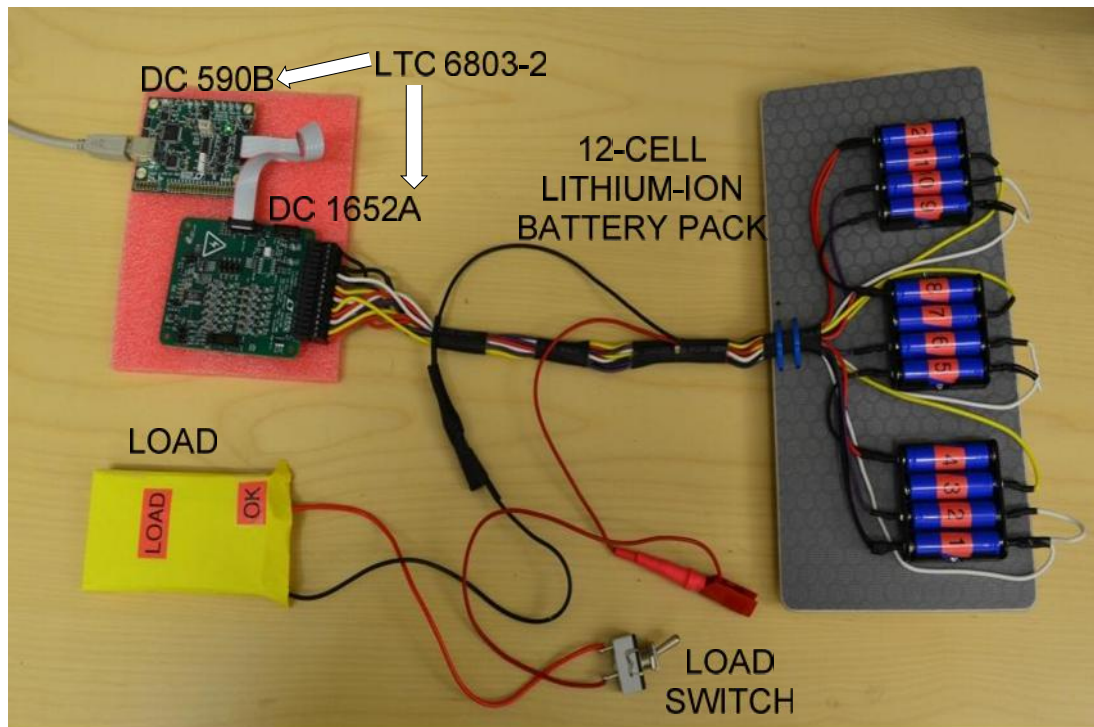
- JP6, JP7, JP8, JP9: All four jumper are set together to position '1'. This setup is for voltage mode SPI daisy chain communication for boards.

The jumpers setup for evaluation board DC590B is quite straightforward that to follow the datasheet.

- JP1, JP2, JP3: Do not install jumpers, make no connections for all these three jumpers.
- JP4: Set the jumper in 'EN' position.
- JP5: Jumper 'SW' is set as 'ON' position, and jumper 'ISO' is also installed on position 'ON' hence the isolated power supply is set as on.
- JP6: Set the jumper in '5V' position. The isolated supply voltage is selected as 5V.

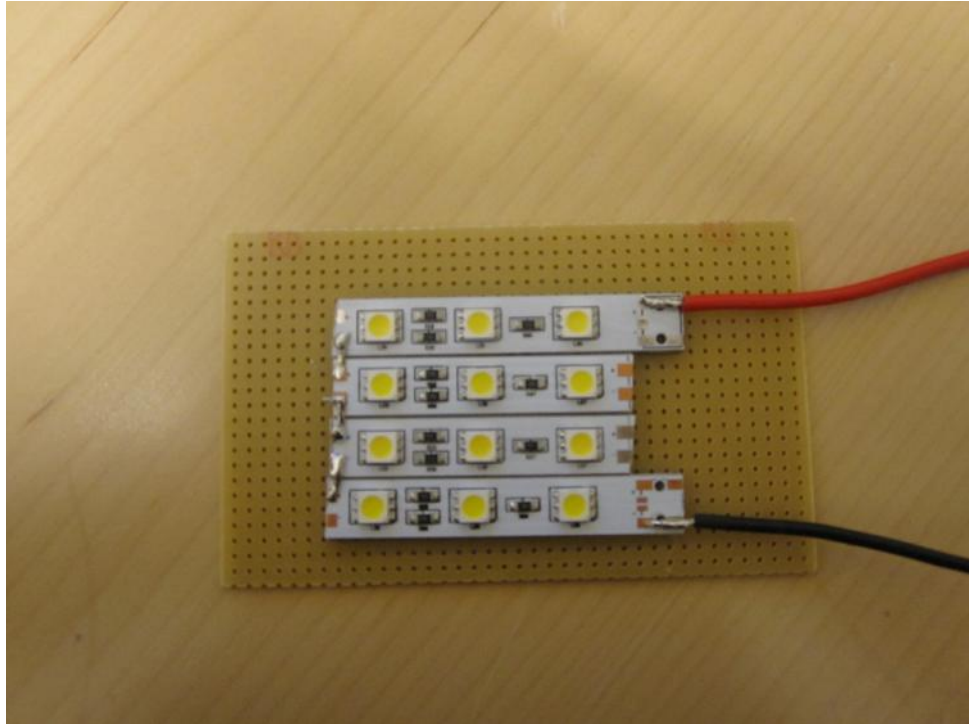
After all the jumpers are installed in the correct positions, connect the demo board DC1652A to evaluation board DC 590B through SPI cable. Then the battery pack is stack into the demo board by plugging the connector socket into cell connector on demo board. After checking all the connections are correct and secure, the system can be powered up by USB port from the host PC.

Then after the boards are connected to host PC by USB port and successfully powered up, ISO PWR LED on DC 590B will be lit, the board is operating. Then commands are set out from host PC, the COMMAND LED will flicker. Figure 3.9 reveals this battery management system configuration in hardware.

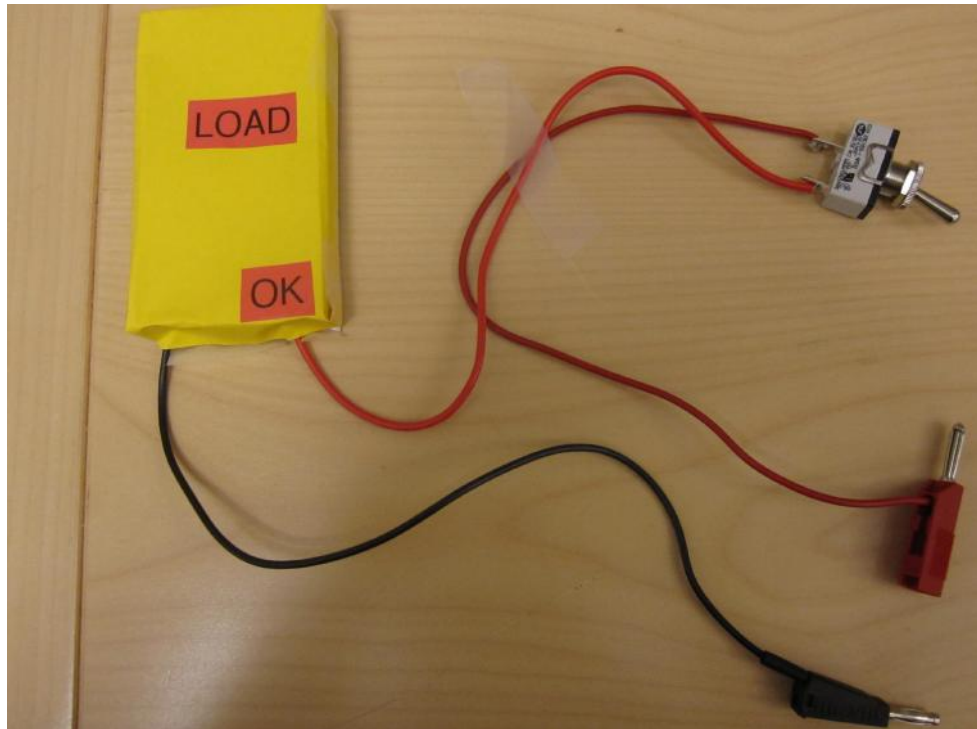


**Figure 3.9.** The real Battery management system configuration in hardware

Furthermore, for the sake of testing battery discharging performance, an external load is also built up. The load is comprised with four LED strips connected in series on a PCB, and each of them has three diodes and three resistors on it. Every one of the resistors has a resistance of  $150\ \Omega$ . The load is supposed to undertake 48V's voltage and able to conduct a current of 50mA.



**Figure 3.10.** LED load configuration on PCB



**Figure 3.11.** Construction of the load for battery pack

After the strips are stuck on to PCB firmly and soldered in series, two wires are led from the two terminals. Similarly according to the common sense, the most positive potential is labelled with red wire while the most negative potential with the black one. These two wires are later connected to the two terminals of battery pack when discharging is needed, with colour corresponding. Then a box with cover is built up for both protecting the PCB load and reducing the luminance for users. Furthermore, a switch is connected in series as well for the sake of circuitry protection. The configuration of the load is represented in Figure 3.11.

## 4. SOFTWARE GOALS AND STURCTURE

The main task of this project is to monitor the battery pack in real time and give an accurate feedback of cell voltage, cell SoC, pack voltage, and pack SoC in real time, and furthermore to conclude the cell status and pack status. Consequently, a well-designed graphic user interface(GUI) is convenient and necessary for users to check and control the battery condition, which are also the goals of software application design. Although Linear Technology provided with a fully functional GUI, we would like to have an individual one which can be modified and controlled by users flexibly. Besides, the GUI provided by LTC cannot show the state of charge(SoC) of batteries. The goals of the software design are concluded as below

- Provide the accurate voltage measurements and the corresponding SoC based on look-up table for each cell in real time.
- Based on the cell voltages determine the cell status.
- Sum up 12-cell's voltage in each time point and display the battery pack voltage, as well as the pack SoC and pack status in real time.
- Present cell voltage and cell SoC in form of chart so as to show the changing process of cell capacity during the time.
- Record the measured cell voltages and SoC in an excel file with each time point.
- Ensure the system is stable enough to measure and record batteries' capacity and evaluate their performance for a fully discharge process.

The software design supports GUI which displays voltage, SoC and battery performance status for each single cell, also provides charts explicating both cell voltage and SoC in real time, also has these measurement results recorded in Excel. In the GUI design, Java language is applied for the interface building up and data communication. Considering the convenience and intuition of application, it is NetBeans that is utilized as the platform to implement all functions.

In software design, first of all a project named BMSPenny is built up. Then such independent public class *Commport*, *GUI*, *Bms*, *ChartVoltage* and *ChartSoC* are built up correspondingly. Among them, the communication of LTC with host PC through USB port is defined in class *Commport*, besides the calculation method of battery cell state of charge and method of generating an excel file are both defined in this class; class *GUI* is dedicated in the graphical user interface design, both from patterns and function. Class *ChartVoltage* and *ChartSoC* generate the charts of cell voltage measurements and its state of charge respectively. Finally, a class *Bms* defines the main commands and calls the methods in all classes.

### 4.1. LTC serial communication to PC

LTC 6803-2 provides an addressable serial interface to control processor through USB port. From the device manager, the USB ports of the host PC can be found, and port 'COM9' is determined to be used.

First of all, configuration registers for read and write, start measurement, cell reading and device manufacture ID are defined. Also the LTC communication port should be defined. For some parameters that are hidden from other classes within the package, such as the USB communication port, the buffered reader for USB to serial input data and the USB to serial output stream are defined as private static. It also defines that it would take 2 seconds to wait for an open port and 9600 bits as default per second for the USB COM port as well.

Then in the method of *initialize()* the communication from USB to serial is defined and initialized. The LTC port is set from command line, and port identifiers are obtained. After 2 seconds wait time, the port is open, and then the serial port parameters need to be set.

After that, the USB to serial input data reader port "*ltcInputReader*" and output stream port "*ltcPortOutput*" are open and the data are read at every second.

At last, all the data read are then written into the corresponding registers respectively, the communication from USB to serial port is defined completely. The details of the communication process is described in datasheet of LTC 6803-2, which can be referred in [17].

### 4.2. Cell voltage read and calculation

When the battery pack is connected to the board and the measurement is executed, the ADC of LTC 6803-2 begins to detect the cell voltages and for every time cycle gives an output of 12-bit code with an offset of 0x200, which equals to 512 in decimal. Then conversely, according to this 12-bit ADC measurement output code, the actual cell voltage is obtained as

$$V_{cell} = (C_x V - 512) \bullet V_{LSB} \quad (3)$$

where  $C_x V$  is the decimal ADC measurement for each cell, with an offset of 512, and  $x$  indicates the cell number. After the 12-bit code is obtained from ADC output, it is then converted into integer so as to receive the value of  $C_x V$ . The  $V_{LSB}$  is the resolution of ADC measurement value with regard to the real cell voltage. Since the input voltage range for ADC is from -0.768V to 5.376V, for a 12-bit code the resolution is obtained as

$$V_{LSB} = (5.367 - (-0.768)) / 2^{12} = 1.5mV \quad (4)$$

Buffered reader for USB port to serial port interface reads the input data from board. After the communication from USB to board is successfully established, the input data is then printed out every time cycle, from which each battery cell takes out an individual

3 bytes hexadecimal data (12 bit in all) in a specialized sequence based on datasheet of LTC6803-2. These cell data are then converted into integer thus to retrieve the ADC measurement value  $C_x V$ .

The obtained decimal result of all 12-cell voltages are assigned to 12-bit double array called *cellVoltage* in java class *Bms*, which are utilized for SoC calculation and later loaded on GUI, chart and excel.

### 4.3. State of charge (SoC) estimation

Due to the technical limitation of existing electrical boards, estimation based on cell open circuit voltage is applied. Referring back to Figure 2.2., the discharging curve is depicted in respected with state of charge, and that is what we can employ to make the SoC estimation. Additionally, in accordance with battery discharging characteristics, descent rate of SoC is sharper for both full charge and empty charge sections, whereas the curve tends to be quite flat for other parts. Hence, with regard to a constant interval of 5% for SoC, at full charge section the variations of voltage are set to be larger, and gradually drop approaching to the flatness, and vice versa for empty charge part.

As a result, a set of approximated data regarding SoC versus cell OCV is built, which is represented in Table 4.1. below. In the software programming, this estimation method is loaded on the ‘*Commport*’ class.

**Table 4.1** Look-up Table for Cell SoC Estimation Based On Cell OCV

Cell OCV(V)	SoC
[4.2-4.1)	100%
[4.1-4.05)	90%
[4.05-3.99)	85%
[3.99-3.945)	80%
[3.945-3.983)	75%
[3.983-3.847)	70%
[3.847-3.812)	65%
[3.812-3.7755)	60%
[3.7755-3.7405)	55%
[3.7405-3.670)	50%
[3.670-3.658)	45%
[3.658-3.618)	40%
[3.618-3.565)	35%
[3.565-3.505)	30%
[3.505-3.430)	25%
[3.430-3.350)	20%
[3.350-3.240)	15%
[3.240-3.140)	10%
[3.140-3)	5%
[3-0]	0

According to this look-up table, state of charge for every single cell can be obtained. Dividing the sum total of SoC of the whole pack by the number of cells, namely, 12, thus obtain the average SoC of the whole battery pack. In class ‘*Commport*’, the obtained 12 voltages of the whole battery pack are stored in array ‘*cellVoltage*’ in sequence. Through this estimation method, every cell voltage is then calculated to its relevant SoC and the result is stored in a length-of-12’s array ‘*cellSoc*’.

#### 4.4. Voltage and SoC charts

In the graphic user interface designing, cell voltage and SoC are renewed every second, and the old data would be cleared. However, we also would like to extract elaborate statistics variations of cell voltage and SoC in real time in order to compare how the changes of batteries’ performance. Therefore, the charts of voltage and SoC are necessary.

The voltage chart and SoC chart are designed in two individual windows, in order to give a more vivid representation. For the voltage chart, the data of each cell that are taken from the array ‘*cellVoltage*’ are plot on chart in time series, as format of “HH:mm:ss”, and likewise for SoC chart.

In configuration, JFreeChart[25] is utilized to develop a professional and high quality chart and class ‘*TimeSeries*’ is applied to represent a sequence of data items in form of time period. The main purpose of application of ‘*TimeSeries*’ is to ensure all data with the same type of time format, as well as no more than one time appearing at each period. Both of these two charts would be loaded on graphic user interface in shift by clicking the related buttons, and voltage chart will show by default after clicking the execute button.

#### 4.5. Graphic user interface design and update

##### 4.5.1. Layout design of GUI




The designing goal for GUI is to display the function of BMS as well as providing simple control of it. Therefore, the performance of batteries from different aspects needs to be show clearly, based on real time.

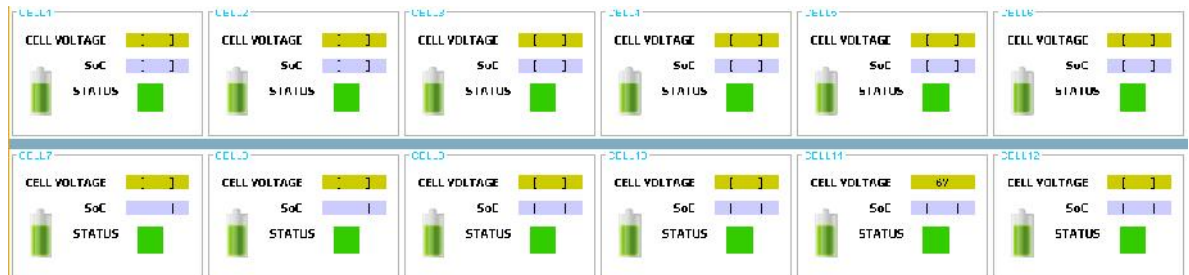
In this graphic design, special class JFrame[26], JLabel[27] and JPanel[28] are used to support different functions. Where JFrame gives the basic layout for the whole interface, JPanel provides different kinds of panels added onto the layout, while the JLabel supports labels, icons, and text on layout and panels.

For the batteries, we would like to show their cell voltages and cell SoC in real time, meanwhile both of them need to be shown as a status icon updated in real time. Such status is determined by battery cell SoC, and Table 4.2 below shows in details how the cell status is defined as battery icon, and Figure 4.1 shows how the panel is designed for battery cells part.

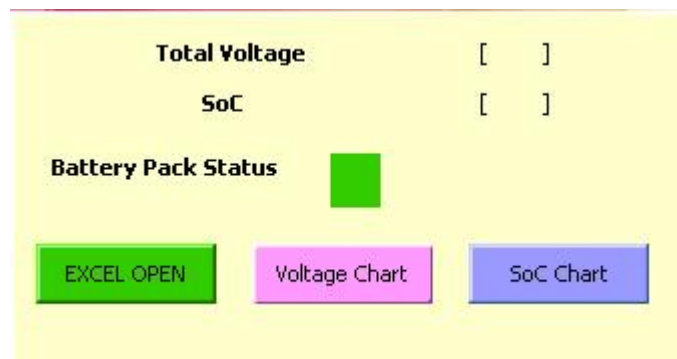


*Table 4.2 Cell status as regards with battery icon*

Cell Status	Full	good	half	low	warn
Battery icon					
Cell SoC	100%-90%	90%-60%	60%-30%	30%-5%	5%-0%

*Figure 4.1. Panel design for each battery cell*

Then, another two new JPanels are loaded on frame. One of them reveals the measurement results of the whole pack, with four JLabels indicating battery pack voltage and SoC for 12 cells, as well as a JPanel which is set as green as default showing the pack status. Three JButtons are loaded with mouse click actions enabled. These buttons are for excel file open, voltage and SoC charts shifting respectively. Another panel is designed so as to explain the colours of status panel, namely, green for good, red for over voltage, and yellow for under voltage. The threshold values for over voltage and under voltage are set to be 4.2V and 3V respectively for lithium-ion battery. If a battery cell voltage goes beyond this range, its status panel would show red or yellow to give warning to the users, so as for the whole battery pack. This is shown in Figure.4.2.

*Figure 4.2 Legend panel on GUI design*

Then another panel is added to the frame to show the chart and finally a background is loaded as well. So far so good, the layout design and arrangement are completed in

this way. In the GUI class, on the corresponding source part, there generates the reciprocal codes for the labels, properties and positions of those utilized JLabels, JPanelles and Jbuttons. Such codes are only revisable on design part.

#### **4.5.2. Measurement data updating on GUI**

The GUI is supposed to represent the updated measurement results in every time cycle. As mentioned, the measurement results are saved in array *cellVoltage* and *cellSoC* in double form, and these data are quoted to the cell voltage labels and SoC labels for each respectively.

After the layout design is finished, a method called 'update' is established following the generated code on source part, including all the statements for data updating. The software reads the value from the batteries and makes the decision. If the value is in the normal range, between 3V to 4.2V which is predetermined, it gives a green panel, otherwise it gives a warn, yellow for undervoltage(<3V) and red for over voltage(>4.2V).

As shown in Figure 4.3, when the system is operating, GUI then begins to record the battery voltage and SoC for each cell. Meanwhile it gives the decision result of each battery's performance. Additionally, a chart also shows up to report cell voltages and SoC in real time.

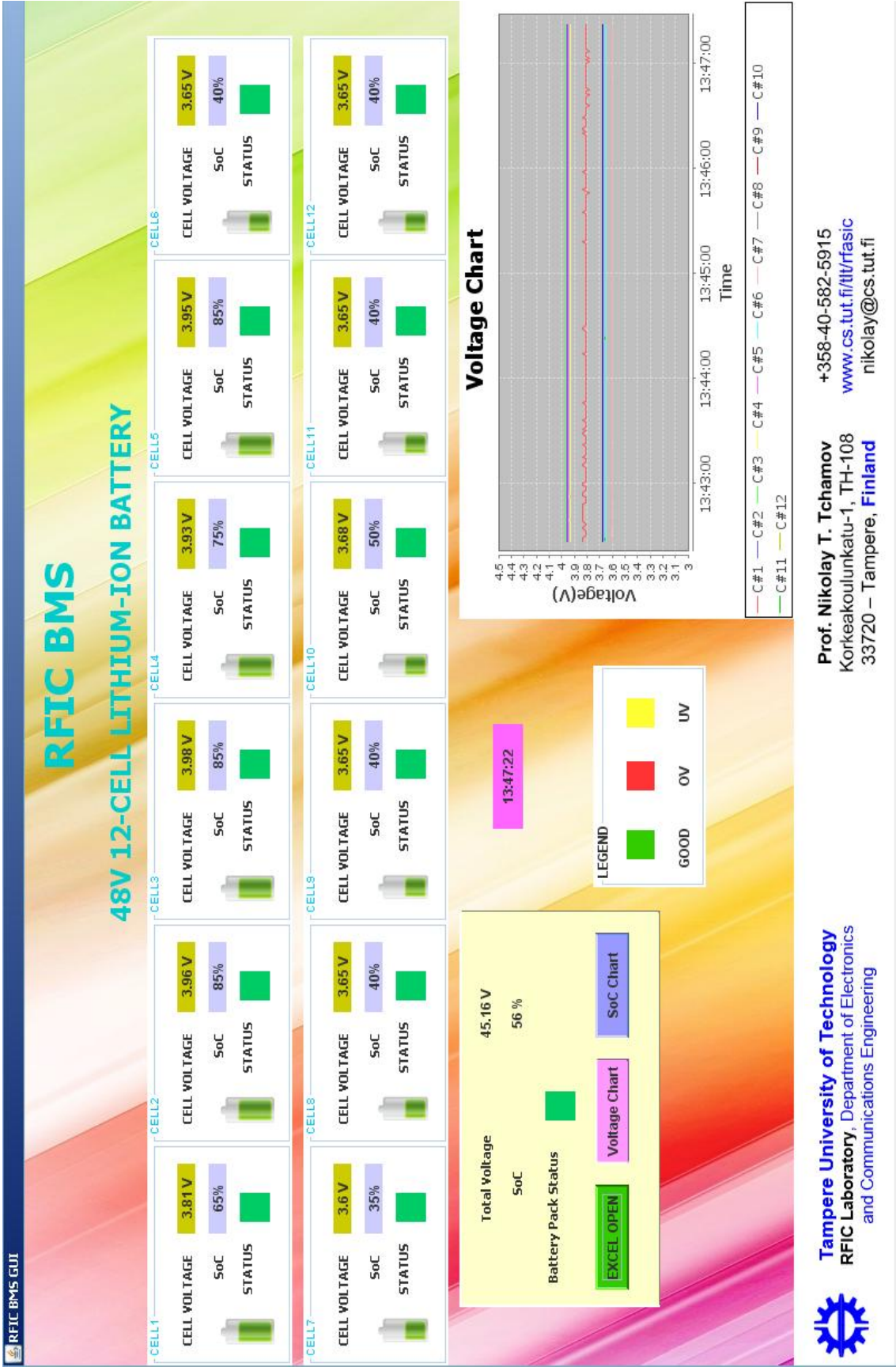
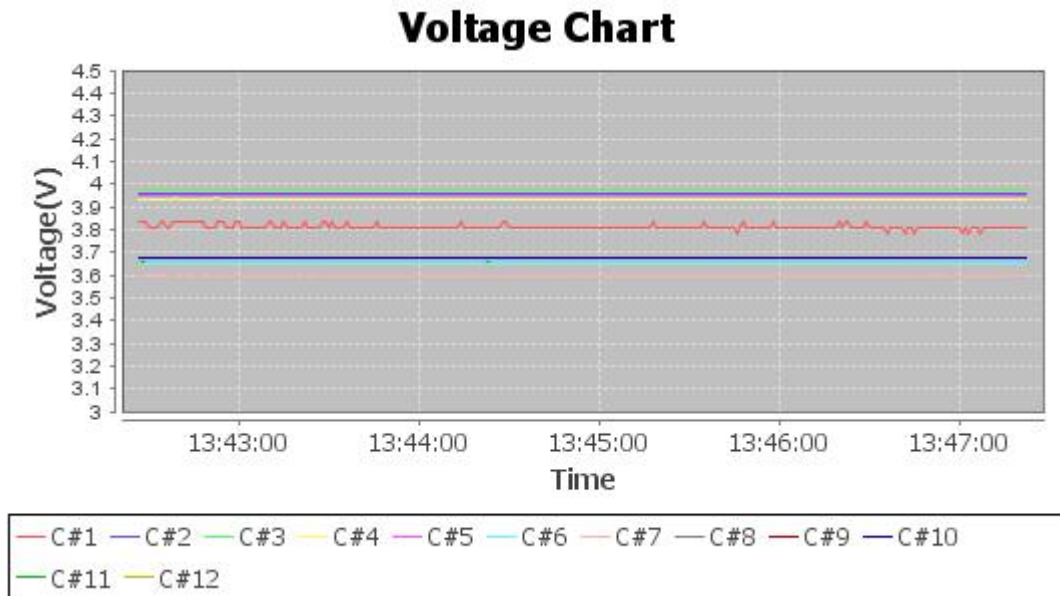
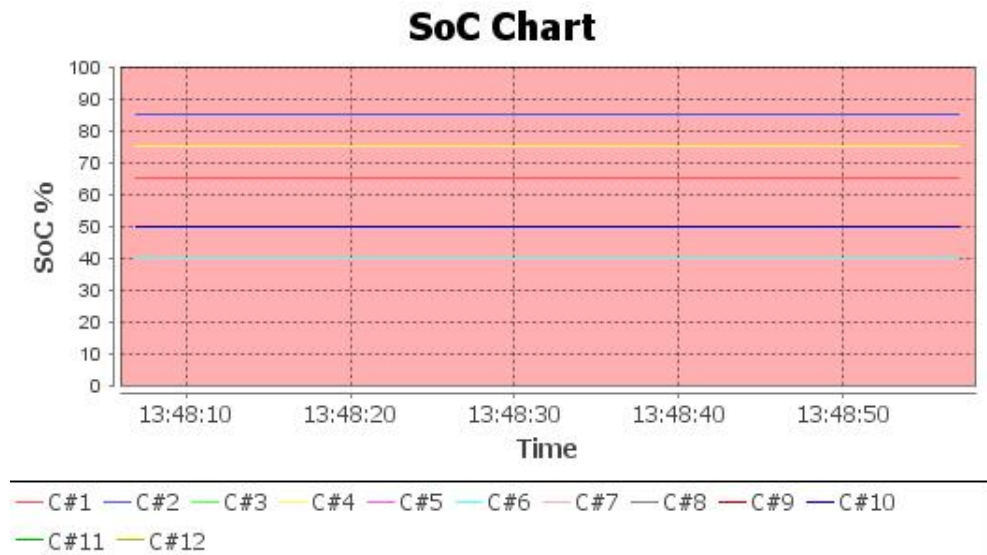


Figure 4.3. Graphic user interface with voltage chart



**Figure 4.4.** Voltage chart design on GUI

The graphic user interface would be renewed every second, and the voltage and SoC chart display the variations of battery status in real time. The overdue data would be deleted after 120 minutes in order to avoid crashing the project. As shown in Figure 4.3., voltages, SoC and battery status of every single cell and the whole pack are well represented as expected, voltage chart is displaying as default. Clicking button 'SoC chart' would reveal the SoC chart, shown in Figure 4.5.



**Figure 4.5.** SoC chart design on GUI

## 4.6. Data record in Excel

In order to record all the measurement results in real time, an excel file is built up to store up to 25000 data. The data is read from the array *cellVoltage* and *cellSoC* and then

are written into the excel cells with real time. This file is named as BMS, and saved automatically in

*d:\Documents and Settings\User\My Documents\NetBeansProjects\BMSPenny.*

After the project is executed, the array begins to write in the measurement data every second and update the new measured results. These results are written into the excel file simultaneously, with maxim written times set as 250000, which means the measurement data is limited to 250000. After the execution is pause by clicking the button, click EXCEL OPEN button, and an excel file with all the measured data from the beginning will open. If the data measured exceed 250000, GUI would give a feedback and excel stops recording the data measurement.

## 5. TEST AND VERIFICATION

The accuracy of the system measurement should be tested and verified. Considering the resolution issue and simplicity, the cell voltage measurements are compared with multimeter. The digital multimeter that is used for test is in type of MS8221D from mas-tech. Voltage range of 20V is used and its accuracy is  $\pm(0.5\%+1)$  according to the datasheet[24].

Due to the resolution and ADC calculation error, there exist differences between the measurement results of both methods.

Table 5.1. records the measurement results both from BMS shown on GUI and from multimeter manually. Batteries are loaded for discharging and batter voltages are measured every other couple of minutes. As what was introduced before, LED strips will be applied as the load. Every one of the resistors in series with LED has a resistance of 150 . The load is supposed to undertake 48V's voltage and able to conduct a current of 50mA.

Both of the measurement were operated at the same time point for the exactitude. Besides, in order to show the original measurement results from calculation without decimal correction, commands are written by JAVA and these results are printed on screen.

**Table 5.1** 12-Cell battery voltages measurement comparison of BMS and voltage multimeter at the same time point

	<b>BMS(without decimal correction)(V)</b>	<b>BMS(corrected to two decimal place)(V)</b>	<b>Multimeter(V)</b>
<b>Cell1</b>	4.0875	4.09	4.08
<b>Cell2</b>	4.1475	4.15	4.15
<b>Cell3</b>	4.1625	4.16	4.16
<b>Cell4</b>	4.1055	4.11	4.10
<b>Cell5</b>	4.1535	4.15	4.16
<b>Cell6</b>	4.1445	4.14	4.14
<b>Cell7</b>	4.0620	4.06	4.06
<b>Cell8</b>	4.1520	4.15	4.14
<b>Cell9</b>	4.1205	4.12	4.12
<b>Cell10</b>	4.0410	4.04	4.03
<b>Cell11</b>	4.1340	4.13	4.13
<b>Cell12</b>	4.1460	4.14	4.14

## 5.TEST AND VERIFICATION

From the table it can be read the maximum measurement difference between BMS and multimeter is 0.01V.

Besides, another measurement comparison on only one cell for different time points is made for a better convince. The pack is loaded for discharging about one and half hours, and every 10 minutes a measurement is operated hence with 10 measurement samples. Cell 4 is randomly selected as a sample, and Table 5.2 records the measurement.

**Table 5.2** Battery voltage measurement comparison of BMS and voltage multimeter at on cell 4 in time series

	<b>BMS(corrected to two decimal place)(V)</b>	<b>Multimeter(V)</b>
<b>11:00:00</b>	4.11	4.10
<b>11:10:00</b>	4.02	4.02
<b>11:20:00</b>	3.99	3.99
<b>11:30:00</b>	3.96	3.95
<b>11:40:00</b>	3.93	3.93
<b>11:50:00</b>	3.91	3.91
<b>12:00:00</b>	3.89	3.88
<b>12:10:00</b>	3.88	3.87
<b>12:20:00</b>	3.86	3.86
<b>12:30:00</b>	3.85	3.85

From this table it can be seen the maximum measurement difference between BMS and multimeter is still 0.01V.

Therefore, according to the analysis above, the cell voltage measurement result of BMS can be trusted. Its measurement error compared with multimeter is in the range of 0.24% to 0.3%.

## 6. CONCLUSION

This thesis introduced the background theory of lithium-ion batteries, and the application, system configuration, measurement and test of a battery management system.

In this thesis, a 12-cell lithium-ion battery pack is built up which is able to provide an output of 48V. Battery cells are connected in series, and each cell has a nominal voltage of 3.7V. The battery monitor LTC 6803-2 undertakes the mission to measure battery cell voltages and monitor battery's performance. All the information are given as a feedback of battery cells' operating status, and are displayed on the graphic user interface designed. For every single cell, its voltage, state of charge and current status are updated continuously on the GUI in time series. Besides, the total voltage of the entire battery pack and its relevant state of charge, as well as the working status, are also illustrated on GUI. What's more, the cell voltage and the state of charge are also well recorded in a form of chart, in order to elaborate how it performs as the time passed. Also an excel file is built up recording all these data labelled with time point.

The system implemented is capable to charge the battery cells, supervise the battery working conditions, and to discharge batteries to an expected capacity. The measurement results give a reasonable accuracy and can be accepted. The block diagram of the entire system is represented in Figure 6.1, blocks inside of the green dashed line are the ones that are already accomplished in this project.

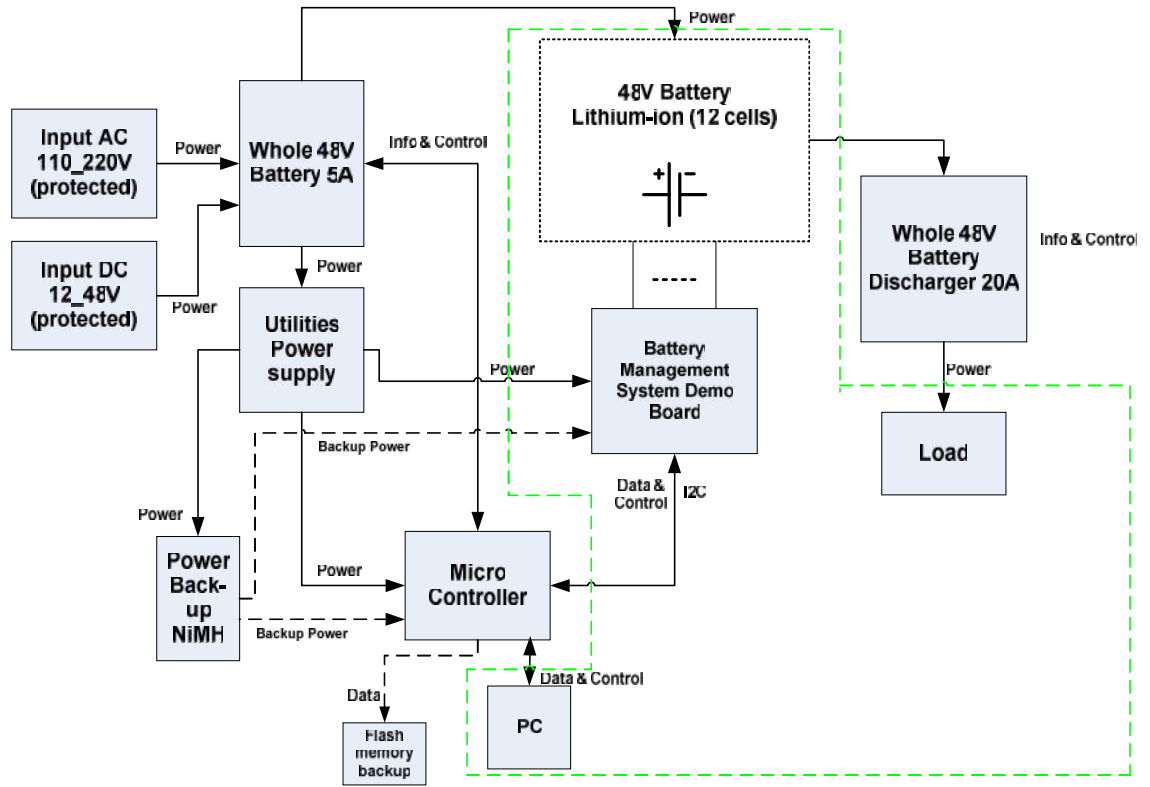
However, there is still some work that is supposed to fulfil in the future. A more expound study on battery inner condition such as internal resistance needs to be studies. A more complex battery management system with DC/DC converters is supposed to be configured. In order to construct a complete and systematic BMS possessing with function of monitoring, balancing, controlling and powering up, there are more modules in need to provide the whole function.

The 12-cell battery pack is charged by either AC or DC, both of which are circuit protected. AC power input provides a constant current of 110mA that is controlled by current limiter, whereas the DC input gives a constant 48V voltage protected by voltage limiter. Notice that the AC or DC power does not go directly to the battery pack, it works as the input for the charger.

Battery management system demo board is the key module to talk to the battery cells in the most direct way. It detects the batteries performance and presents the most intuitive and prompts feedback to the user port. All the commands talking to batteries are received and executed in this module. It is the bottom level of module which executes the commands.



The microcontroller provides a communication channel for the host PC to set out the commands to control the BMS board as well as to receive a feedback from the BMS to monitor the battery performance. It is the module which processes the commands. The communication interface between microcontroller and BMS demo board is based on I<sup>2</sup>C.



**Figure 6.1.** Block diagram of the completed BMS for future work

In the future research, based on micro-controller as a core, a more smart battery management unit would be implemented to obtain a more accurate voltage measurement, especially for the SoC calculations. Besides, it would be comprised with temperature measurement unit, to give a battery temperature monitoring as well. The whole BMS would further achieve a self-controlling function. For the cells balancing unit the system is able to detect the misbalance and make the decision on equalization methods. Thus, the battery management system would be able to achieve all function in a more intelligent way.

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